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TDR-63-231

# Airborne Instrumentation System for Measuring Meteorological Phenomena Inside Thunderstorms

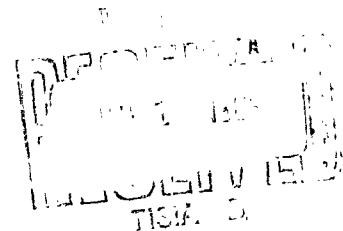
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TECHNICAL DOCUMENTARY REPORT NO. ASD-TDR-63-231

May 1963

Directorate of Flight Test  
Aeronautical Systems Division  
Air Force Systems Command  
Wright-Patterson Air Force Base, Ohio

Project No. 8620, Task Nos. 862001, 862005



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## FOREWORD

This report was prepared by 1st Lt George P. Royce, project engineer, of the Adverse Weather Branch, Flight Test Engineering Division, Directorate of Flight Test, Deputy for Test and Support, Aeronautical Systems Division (ASD), Wright-Patterson Air Force Base, Ohio, under Project 8626-862001, "Thunderstorm Electricity," and 8670-862005, "Cloud Structure Dynamics." Captain Joseph G. Kondracki was pilot of the F-100F test aircraft and Captain Harvey J. Royer was pilot of the T-33, both of whom are assigned to the Fighter Operations Division, Directorate of Flight Test.

The program described in this report was a joint research effort by the U. S. Weather Bureau (USWB), Federal Aviation Agency (FAA), Air Force Cambridge Research Laboratory (AFCRL), and ASD. Flight operations were conducted in conjunction with the National Severe Storm Project (NSSP) nicknamed "Rough Rider," during May and June 1962 in Oklahoma City, Oklahoma. NSSP is a multiyear project directed by the USWB (Mr. C. R. Van Thullen, Director).

ASD designed, fabricated, procured, and installed instrumentation to measure meteorological phenomena inside severe local storms. Data will provide information for research meteorologists and weather forecasters. NSSP coordinated the entire research program, forecast weather during the test period, archived the data, and provided technical direction with regards to meteorology. AFCRL fabricated the electric field strength measuring equipment for an ASD aircraft, and provided technical advice on meteorology and methods of measurement. FAA provided funds for purchase of instrumentation (as concerned with ASD aircraft) and provided radar control facilities and personnel at the test site.

All thunderstorm penetrations were accomplished under the direction of FAA radar controllers Messrs. Howard Murphy and Eugene Traynor assigned to the Oklahoma City RAPCON (radar approach and control center).

The instrumentation of two aircraft for severe storm investigation involved the efforts and time of many ASD personnel. The mention of a few by name does not detract from the efforts of the many others. Ronald Stanford, Flight Test Engineering, was responsible for the idea and means of measuring liquid water content. Vern Rollofson, Directorate of Test Data, was Instrumentation Specialist and responsible not only for choosing and checking out much of the equipment but also for integrating all equipment originating from several sources into one single operating package. Messrs. Henry Maurer and Glenn Grewall, Directorate of Test Data, were responsible for design and fabrication of the cloud particle camera. Captain Russell Hodges, Air Force Institute of Technology, designed the gust vanes to withstand hail and heavy precipitation and still be responsive enough to sense changes in air direction.

ABSTRACT

Equipment to measure meteorological phenomena inside thunderstorms was designed, fabricated, installed, and operated in two jet aircraft in conjunction with the National Severe Storm Project in Oklahoma City, Oklahoma. Devices which were used for the first time in this environment were those to continuously measure liquid water content, electric field strength, and hail mass, and to photograph cloud particles. Other parameters recorded were normal acceleration, vertical gust velocity, temperature, and differential static pressure. The data collected during the ASD flight test program are archived with the U. S. Weather Bureau and can be obtained through the National Severe Storm Project.

Publication of this technical documentary report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


  
ROBERT L. COLLIGAN, JR.  
Colonel, USAF  
Deputy for Test and Support

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## INTRODUCTION

## Objective

An F-100F and a T-33 jet aircraft were flown through thunderstorms to measure meteorological phenomena. This report describes the instrumentation, its accuracies, response rates, and shortcomings. Where the data have been treated in certain ways, the means for ultimate use of the information is given. Also provided are summaries of what data were collected on what flights.

## Description of Test Aircraft

The test aircraft, F-100F, S/N 56 - 3744, and T-33, S/N 53 - 5404, were essentially in standard configuration except as described herein. The F-100 (figure 1) carried instrumentation in both gun bays, both expended link bays, several electronics bays, and the forward nose compartment. The cloud particle camera was mounted in a modified external fuel tank. The nose boom was fitted with wind-direction vanes. Numerous static dischargers of a new design were mounted on the wings and empennage. The engine was equipped with pilot-selected continuous ignition.

The T-33 (figure 1) carried instrumentation in the rear cockpit in place of the seat. A nose boom for wind-direction vanes was mounted in one of the gun ports. The cloud particle camera was installed in a modified chaff dispenser under the left wing.

Other aircraft characteristics were:

|                                  | <u>T - 33</u> | <u>F - 100</u> |
|----------------------------------|---------------|----------------|
| Wing area, sq ft                 | 237           | 400            |
| Wing span, ft                    | 39            | 39             |
| Gross weight, lb (No fuel)       | 10400         | 23500          |
| Aspect ratio                     | 6.4           | 3.9            |
| Mean aerodynamic chord, ft       | 6.75          | 11.15          |
| Maximum acceleration limits, g's | +6,-3         | +6,-3          |

## AIRBORNE RECORDED PARAMETERS

Data collected from and in conjunction with the ASD test program, including the computer print-outs and cloud particle photographs, can be obtained through the National Severe Storm Project, U. S. Weather Bureau. The following summarizes the information available from the ASD program.





Figure 1. F-100 and T-33 Test Aircraft

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## From the F-100 System

|               | Gust<br>Vel | Norm<br>Accel | Temp | Liq Water<br>Content | Alt | Air<br>Speed | Particle<br>Camera |
|---------------|-------------|---------------|------|----------------------|-----|--------------|--------------------|
| 8 May         | x           | x             |      | x                    | x   | x            | x                  |
| 20 May, Flt 1 | x           | x             |      | x                    | x   | x            | x                  |
| 20 May, Flt 2 | x           | x             |      | x                    | x   | x            | x                  |
| 24 May        |             | x             |      |                      | x   | x            | x                  |
| 31 May, Flt 1 |             |               |      |                      |     |              |                    |
| 31 May, Flt 2 |             | x             | x    | x                    | x   | x            |                    |
| 5 June        |             | x             | x    | x                    | x   | x            | x                  |

## From the T-33 System

|               | Gust<br>Vel | Norm<br>Accel | Temp | Alt | Air<br>Speed | Diff<br>Pres | Hail<br>Impact | Particle<br>Camera |
|---------------|-------------|---------------|------|-----|--------------|--------------|----------------|--------------------|
| 20 May, Flt 2 |             | x             |      | x   | x            | x            | x              | x                  |
| 22 May, Flt 1 | x           | x             | x    | x   | x            | x            | x              | x                  |
| 23 May        | x           | x             | x    | x   | x            | x            | x              | x                  |
| 24 May        |             | x             | x    | x   | x            | x            | x              | x                  |
| 30 May        |             | x             |      | x   | x            | x            | x              |                    |
| 31 May, Flt 1 |             | x             |      | x   | x            | x            | x              |                    |
| 31 May, Flt 2 |             | x             |      | x   | x            | x            | x              | x                  |
| 5 June        |             | x             | x    | x   | x            | x            | x              | x                  |

Listing of specific parameters in the above tables does not imply that data for all storm traverses made on a particular flight are available. Such information must be obtained from each separate computer print-out (figure 2). Data on the print-outs include the clock time at which each run started (Central Standard Time), whether or not the cloud particle camera operated, the average aircraft gross weight for each run, etc. Note that no comment is made on the quality of individual particle photographs, this decision being left to the respective investigators. Also in the print-outs are pilot comments made during storm penetrations which could be positively related to elapsed time through the use of event markers on the oscillograph record.

Other information directly connected with the ASD flight program, collected during the storm traverses was (1) sketches and photographs of the PPI radarscope presentations; (2) transcriptions of all in-flight radio conversations between the pilots and radar controllers (which includes description of events by the F-100F pilot), and of the T-33 pilot's comments during storm penetrations; (3) transcriptions of certain comments made by radar room personnel during the missions; (4) transcriptions of post-flight de-briefings conducted by ASD flight and ground crews.

|          |                   |                     |               |             |                        |                      |
|----------|-------------------|---------------------|---------------|-------------|------------------------|----------------------|
| AIRCRAFT | DATE              | RUN NO.             | CLOCKTIME     | DROP CAMERA | GROSS WT.              |                      |
| F-100    | 31 MAY, 1962      | 1 OF 4              | 183500C       | NO          | 29,900                 |                      |
| TIME     | PRESSURE ALTITUDE | CALIB. AIRSPEED     | TRUE AIRSPEED | NOR. ACCEL  | VERTICAL GUST VELOCITY | LIQUID WATER CONTENT |
|          |                   |                     |               |             |                        | AMB. TEMP.           |
| SEC.     | FT.               | KTS.                | KTS.          | G           | FT./SEC.               | #WATER / #DRY AIR    |
| XXX.X    | XXXXX.            | XXX.                | XXX.          | X.XX        | XXX.X                  | XX.X                 |
|          |                   |                     |               |             |                        | XX.                  |
| AIRCRAFT | DATE              | RUN NO.             | CLOCKTIME     | DROP CAMERA | GROSS WT.              |                      |
| T-33     | 23 MAY, 1962      | 1 OF 10             | 155130C       | YES         | 13,800                 |                      |
| TIME     | PRESSURE ALTITUDE | HAIL CAL. MASS ASP. | TRUE AIRSPEED | NOR. ACCEL  | VERTICAL GUST VELOCITY | AMB. TEMP.           |
|          |                   |                     |               |             |                        | D-VALUE              |
| SEC.     | FT.               | IN. KTS.            | KTS.          | G           | FT./SEC.               | DEG. C               |
| XXX.X    | XXXXX.            | .XX XXX.            | XXX.          | X.XX        | XXX.X                  | XX.                  |
|          |                   |                     |               |             |                        | XXXX.                |

Figure 2. Example of Computer Print-Out, T-33 and F-100

## INSTRUMENTATION

## Design Philosophy

The basic premise of the meteorological instrumentation system was simultaneous measurement of a large number of variables. A further requirement was sufficient ruggedness of equipment to withstand the rigors of flight through thunderstorms. On some instances it was necessary to sacrifice definition and resolution to handle the large magnitudes of several of the phenomena. Combinations of these design criteria made necessary the acceptance of some compromises in quality of data which are explained in applicable portions of the text.

## Aircraft Equipment

The following table summarizes the measuring devices carried on each aircraft:

|  | <u>T-33</u> | <u>F-100F</u> |
|--|-------------|---------------|
| Pitch & yaw vane angle (nose boom)         | x           | x             |
| Normal, lateral, longitudinal acceleration | x           | x             |
| Pitch and roll angle                       | x           | x             |
| Pitch, roll, and yaw angle rate            | x           | x             |
| Airspeed and altitude                      | x           | x             |
| Temperature                                | x           | x             |
| Liquid Water Content                       |             | x             |
| Electric field strength                    |             | x             |
| Differential static pressure               | x           |               |
| Hail mass                                  | x           |               |
| Hail Camera                                |             | x             |
| Cloud particle camera                      | x           | x             |
| Static discharge current                   | x           | x             |

Cloud particle and hail photographs were recorded on their respective films. All other parameters were recorded on 12-inch oscillograph paper running at one-half inch/second. The T-33 was also equipped with a wire recorder for pilot comments during storm traverses.

## Gust Velocity Measurement

The vertical component of gust velocity was calculated using the pitch vane, pitch angle, rate of pitch, normal acceleration, and airspeed. The primary data source was the pitch vane, corrected for aircraft motions through use of the other parameters. The vertical gust component is given by (reference 1):

$$w_g = v(\alpha - \bar{\alpha}) - v(\theta - \bar{\theta}) + l(\dot{\theta} - \bar{\dot{\theta}}) + \int_0^t (\alpha - \bar{\alpha}) dt + w_0 \quad (1)$$

where

- $w_g$  = Gust velocity, ft/sec
- $w_o$  = Initial aircraft velocity, ft/sec
- $V$  = True airspeed, ft/sec
- $l$  = Distance from vane to accelerometer, ft
- $a$  = Normal acceleration, ft/sec<sup>2</sup>
- $\alpha$  = Pitch vane angle, radians
- $\theta$  = Pitch angle, radians
- $\dot{\theta}$  = Pitch rate, radians

The bar denotes an average value of the variable taken over a five second interval (2.5 seconds on either side of the point being calculated). This technique was used to eliminate long wave length effects from turns, roller-coaster maneuvers, gyro drift, etc. In effect, the gust velocity magnitude is "forced" to oscillate about zero. Using this technique prevents analysis of long wave length drafts, but allows more confidence to be placed on the final data when the afore-mentioned unknowns are eliminated. Raw data and the computer program are available at ASD for recalculation if a different value of "traveling" mean is desired.

The term  $l(\dot{\theta} - \bar{\dot{\theta}})$  can be neglected because of its small contribution. Initial aircraft velocity,  $w_o$ , was an average of the integration of normal acceleration,  $a$ , over the first three seconds of record. The records were evaluated at 0.1-second intervals.

The vanes were mounted on a boom extending forward from the nose of the aircraft. They were about six feet in front of the F-100 and about four feet in front of the T-33. Both of the distances should have been greater to decrease the effects of upwash, but problems were encountered in keeping the booms stiff enough. Natural frequencies of the booms were 18 cps and 7 cps for the F-100 and T-33, respectively.

The vanes were constructed of 1/16 inch thick plywood (figure 3) to provide ruggedness in the hail/precipitation environment. Balsa wood vanes used in the 1960 and 1961 thunderstorm projects were unsatisfactory from a structural standpoint, even though they had excellent response characteristics. A degradation in performance was accepted as the price for vanes which would remain intact through the worst storms.

The new vanes had a natural frequency of approximately 25 cps at 210 KCAS and 32 cps at 275 KCAS for the T-33 and F-100, respectively. Damping was 0.7 of critical. They could respond to a 2 ft/sec gust magnitude (reference 2). The velocity values have an overall accuracy of  $\pm 5$  ft/sec.

#### Normal Acceleration and Derived Gust Velocity

Normal acceleration was calculated from the output of accelerometers located 11 feet ahead of the F-100 nominal center of gravity and 10 feet ahead in the T-33. The instruments were less than one foot away from the aircraft center line. Effects of pitch angle acceleration ( $\ddot{\theta}$ ) were insignificant as shown by calculations which took them into account. Accuracy of the normal acceleration value was  $\pm 0.05g$ .

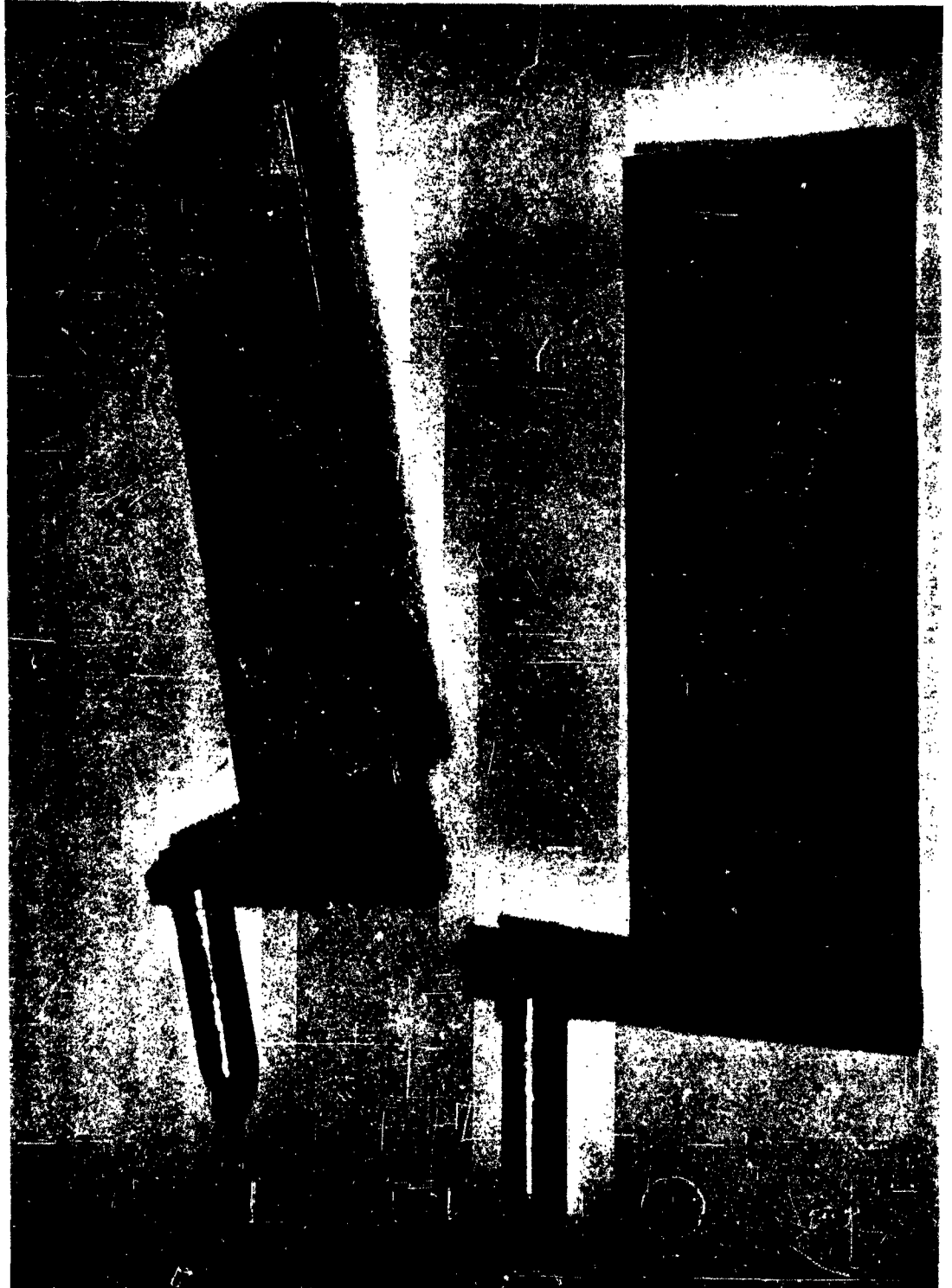


Figure 3. New Plywood Gust Vanes

Derived gust velocities ( $U_{de}$ ) can be calculated according to (reference 3). Incremental accelerations can be obtained from the tabulated data by subtracting  $1g$  from each peak value of acceleration. The remaining information required for  $U_{de}$  can be found thus: weight, airspeed, altitude in the tabulated data sheets; wing area and span (see Introduction); and slope of lift curve in figure 4. Note that equivalent airspeed must be calculated from true airspeed and the density ratio.

#### Airspeed and Altitude

Airspeed and pressure altitude were recorded with a multiple-mirror (SFIM) system which allowed measurements to be made to 2 knots and 20 feet, respectively. Position error calibrations were such that accuracy of measured absolute quantities was  $\pm 5$  knots and  $\pm 100$  feet. However, the changes in airspeed and altitude should be accurate to  $\pm 2$  knots and  $\pm 20$  feet, respectively.

United States Standard Day temperature for the measured pressure altitude was used to calculate true airspeed for all penetrations. Because measured temperatures were not available for all runs, U. S. Std Day temp was used so that all airspeed calculations would be uniform.

#### Temperature

Indicated temperature was sensed with a Rosemount total temperature probe mounted on the forward bottom portion of the fuselage (figure 5). An open wire element was used initially in the T-33. A hermetically sealed element was used throughout the program on the F-100. Heavy icing conditions encountered on one penetration caused the element wire in the T-33 probe to break. Therefore, only sealed elements should be used in this type of flight test program.

Neither one of the probes was heated for anti-icing purposes because of the unknown contribution of the heat to the measured temperature. Since only one probe was on each aircraft, a comparison could not be made of the outputs of heated and unheated equipment.

Ambient temperature was calculated as follows:

$$T_a = \frac{T_i}{1 + K \frac{M^2}{5}} \quad (2)$$

where

$T_a$  = Ambient temperature, °K

$T_i$  = Recorded indicated temperature, °K

$M$  = Mach number

$K$  = Probe recovery factor

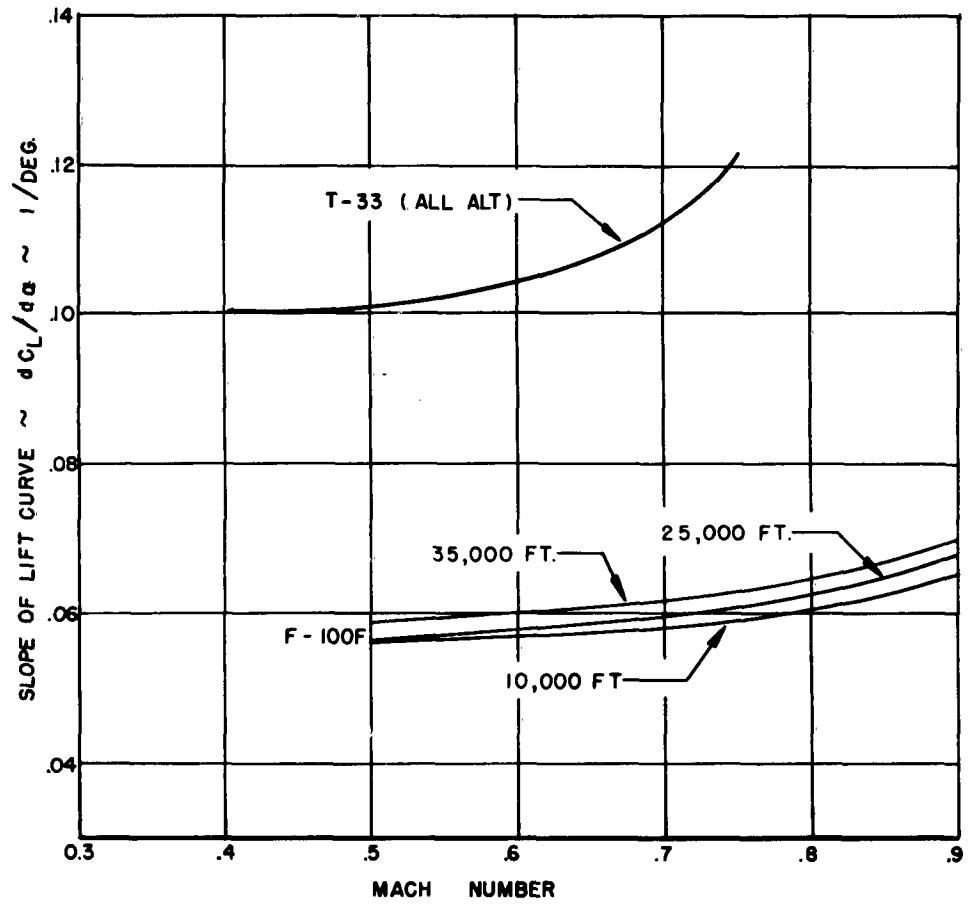


Figure 4. Slope of Lift Curve, F-100 and T-33





Figure 5. Rosemount Total Temperature Probe

Mach number was computed with standard data reduction equations. Values of recovery factor were 0.78 for the F-100 and 0.58 for the T-33. These figures are not high enough (particularly that for the T-33), as recovery factors are generally in the neighborhood of 0.90. Accuracy of calculated ambient temperature is

$$\pm 2\% \text{ (of } T_i \text{ in } ^\circ\text{K}).$$

The open wire element had a time constant of less than 0.1 sec, while that of the hermetically sealed element was about 1.5 sec.

#### Hail Mass

A device to detect impacts of hail and, hopefully, to measure its mass was fabricated as shown in figure 6 (shield slightly damaged). SAE 1045 steel was machined to the shape described in figure 7. Strain gages were mounted near the base of the beam to detect bending strain caused by impacts. The output of the gages was run through a bridge network before being recorded so that only the gage in tension was feeding the galvanometer.

Figure 8 is an example of the recorded output of the strain gages. Distinct impacts can be detected above the "noise" in the trace. This "noise" was attributed to vibration of the beam caused by airflow around the device, and by "tin-canning" of the fuselage skin where the beam was mounted. The galvanometer seems to write in two directions at once because of the rapid oscillatory motion (compared with the paper speed). Impacts are marked with an "X", while the dots indicate maximum trace deflection.

The design of this instrument was undertaken as a feasibility study rather than being constructed as a primary data source. As a result an unsatisfactory calibration was conducted. The data can be used as a hail indicator, both in elapsed time and relative mass. For any one run, where true airspeed can be considered essentially constant, the trace deflections (given in the data print-out) can be used to compute relative hail mass.

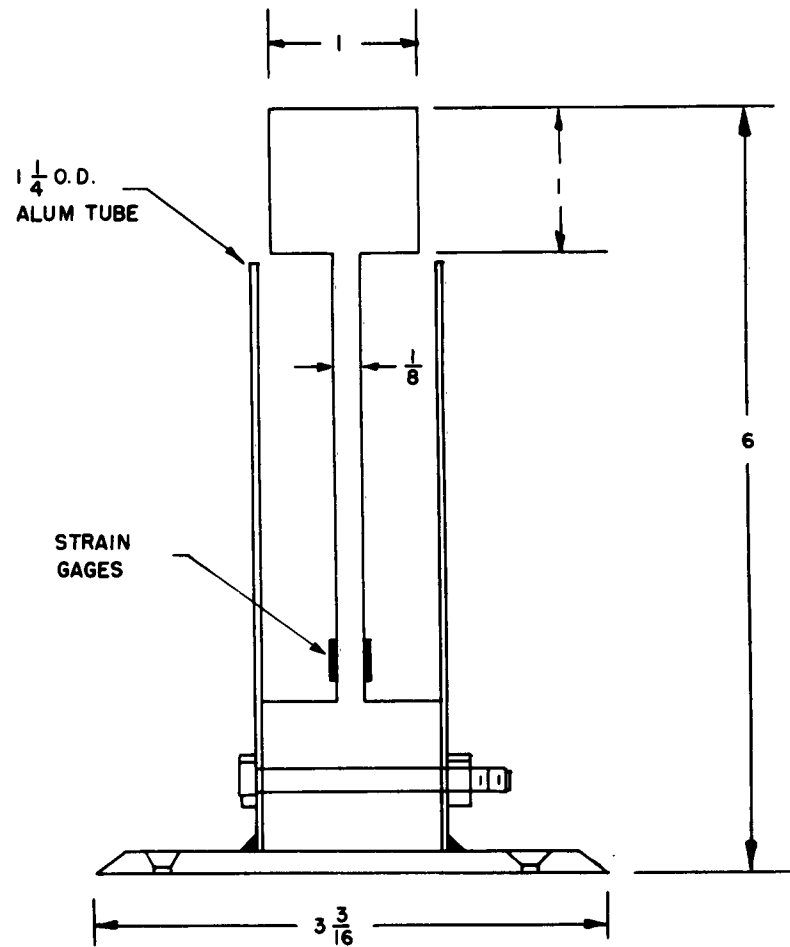
The concept of measuring hail mass in this manner did prove feasible. The protective shield was not protective enough, as evidenced by the damage shown in figure 9. The beam itself was bent out of shape after this flight. The shield was later strengthened by addition of an L-section welded to the leading edge of the cylinder (figure 10).

Assumptions necessary in calculating hail mass are: (1) only one hail particle strikes the face at one instant; (2) airflow is perpendicular to face of beam; (3) all strikes are perpendicular to face of beam; (4) all strikes have point of impact in center of beam face; (5) all kinetic energy of hail particle is transferred to the beam.

With regards to the last assumption, tests conducted at ASD showed the coefficient of restitution between ice and steel to be very small (reference 4). That is, almost all kinetic energy of the hail particle is transferred to the probe in the form of bending potential energy.



Figure 6. Hail Mass Probe



DIMENSION IN INCHES

Figure 7. Dimensional Sketch of Hail Mass Probe



Figure 8. Example of Hail Mass Probe Output



Figure 9. Badly Bent Hail Mass Probe Shield



Figure 10. L-Section Welded to Hail Mass Probe Shield

### Liquid Water Content

The system to measure liquid water content consisted of the aircraft's jet engine and an infrared water vapor analyzer. Solid and liquid water going through the engine was evaporated as the temperature increased during compression of the air. A sample of the mixture in the engine was extracted from the compressor discharge, routed through the infrared device, and its water vapor content determined.

The output of the instrument was the mole fraction of water vapor in the mixture. If  $X$  equals the output, then  $(1-X)$  equals the mole fraction of air in the mixture. Thus  $X/(1-X)$  equals the mole ratio, and when converted to a mass basis

$$w_m = 0.622 \frac{X}{1-X} \quad (3)$$

where

$w_m$  = Mixing ratio (lb water/lb dry air)

This measured amount is the total amount of "free" water in the clouds and the water vapor contained in ambient air. From standard thermodynamic psychrometric relationships (reference 5)

$$w_a = 0.622 \frac{P_v}{P_a - P_v} \quad (4)$$

where

$w_a$  = Mixing ratio in ambient air (lb water/lb dry air)

$P_v$  = Vapor pressure of water vapor at given temperature (lb/sq in)

$P_a$  = Atmospheric pressure (lb/sq in)

If the air inside the storm is assumed saturated,  $P_v = P_g$ , where  $P_g$  equals the saturation pressure for a given temperature

$$w_a = 0.622 \frac{P_v}{P_v - P_g} \quad (5)$$

This in turn makes the "mixing ratio" of liquid and solid water entering the engine to be

$$w_L = w_m - w_a \quad (6)$$

If the mixing ratio,  $w_L$ , is divided by the specific volume of dry air at the measured pressure and temperature, liquid water content of the air in the storm can be determined.

$$v = \frac{53.298 (1 + 460)}{P_a - P_g} \quad (7)$$



where

- $t$  = Ambient temperature, °F
- $P_g$  = Saturation pressure at  $t$ , (lb/sq ft)
- $v$  = Specific volume of dry air, cu ft/lb

It should be noted that at high altitudes, above about 15,000 ft, the water vapor in saturated air is much less than the liquid water found in thunderstorms and probably can be ignored.

The assumptions required for this method of measurement were: (1) all liquid and solid water entering the engine is evaporated before reaching the compressor discharge; (2) a homogeneous sample of the mixture is extracted from the engine; (3) no water is condensed out of the sample as it travels from the engine to the analyzer.

A schematic drawing of the sample handling system is shown in figure 11. The two pressure regulators and the bypass maintained constant pressure and flow rate through the analyzer. In addition the bypass allowed a larger amount of mixture to be drawn from the engine than was required by the analyzer. This allowed the response rate of the engine/instrument combination to be increased somewhat by having a faster flow from the engine to the analyzer.

Figure 12 shows the quarter-inch line (Item A) taking the mixture sample from the engine to the analyzer. Items F and  $P_1$ , figure 12, indicate the filter and upstream pressure regulator. The line, filter, and regulator were heated along the entire length to prevent condensation. The most critical portion was from the engine to the regulator, Item B.

The analyzer (Item A) was mounted under the forward end of the engine (figure 13). Some of the sample handling system can be seen in the foreground attached to the analyzer. The amplifier (electronics needed for the system) was mounted in an unused bay in the fuselage (figure 14, Item B).

Prior to start of flight tests, the device was connected to an engine installed in a test cell at ASD (figure 15). Instrument operation and characteristics were checked and an attempt was made to determine response and accuracy of the engine/instrument combination. The latter tasks were unsuccessful when exhaust stack cooling water of unknown amounts recirculated from the exit into the air inlet stack.

The tests in the engine cell served some purposes: (1) all water going into the engine was evaporated even when large auxiliary amounts were supplied through the test spray rig; (2) the sample handling system performed as required, maintaining pressure and flow rates in the analyzer at preset amounts while engine power was varied; (3) the measuring system sensed changes in water vapor content when engine speed was changed with resultant changes in airflow (and therefore changes in the amount of cooling water being recirculated); (4) heat was needed to prevent condensation in the mixture supply lines.

This system will never be a fast-response method of measuring liquid water content. It did and will handle large amounts of water. Temperature and pressure in the analyzer are critical and must be held constant.

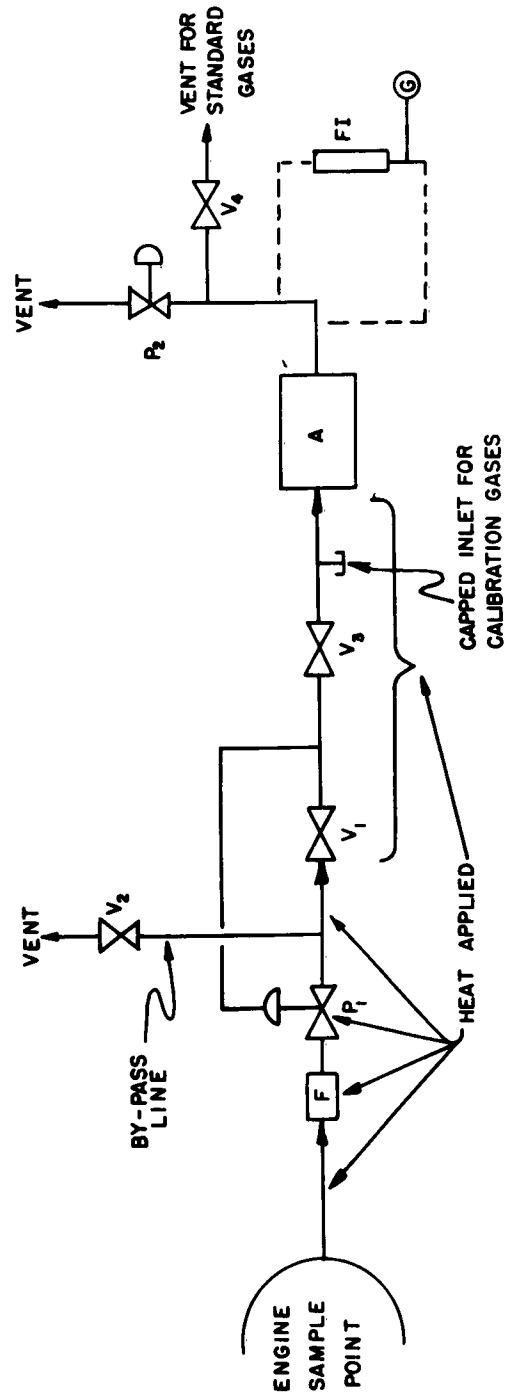
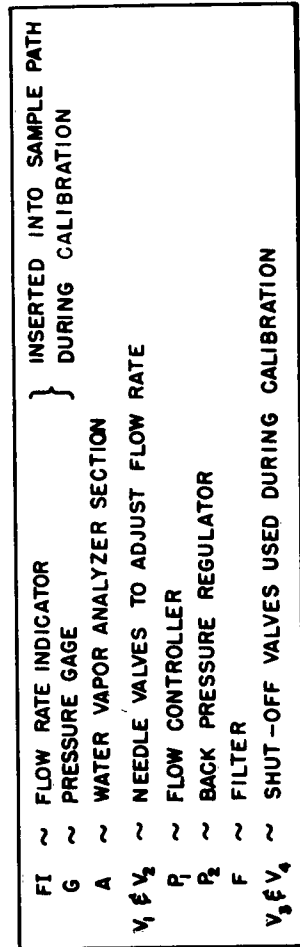


Figure 11. Schematic of Sample Handling System for Liquid Water Content Device

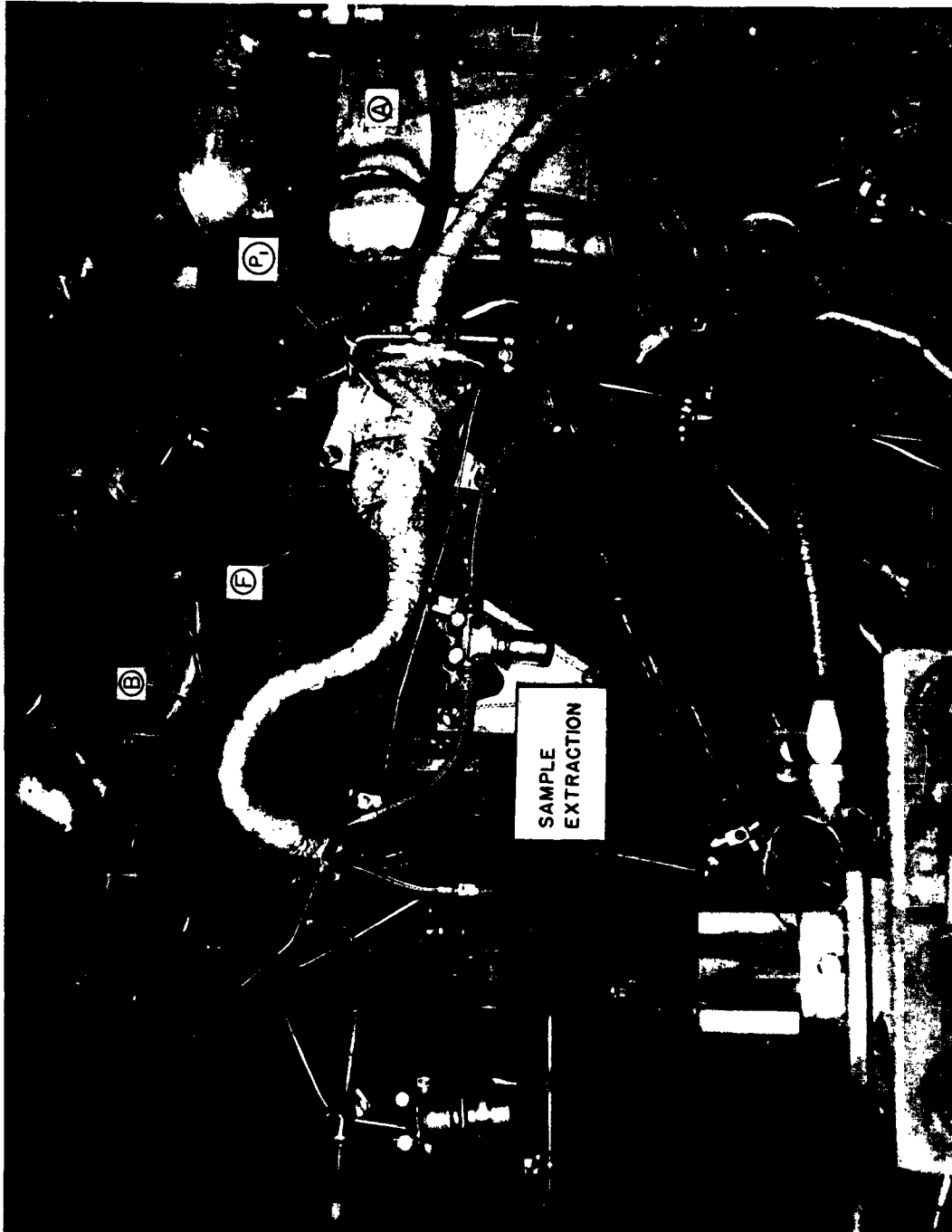


Figure 12. Supply Line on F-100 Engine for Liquid Water Content Device

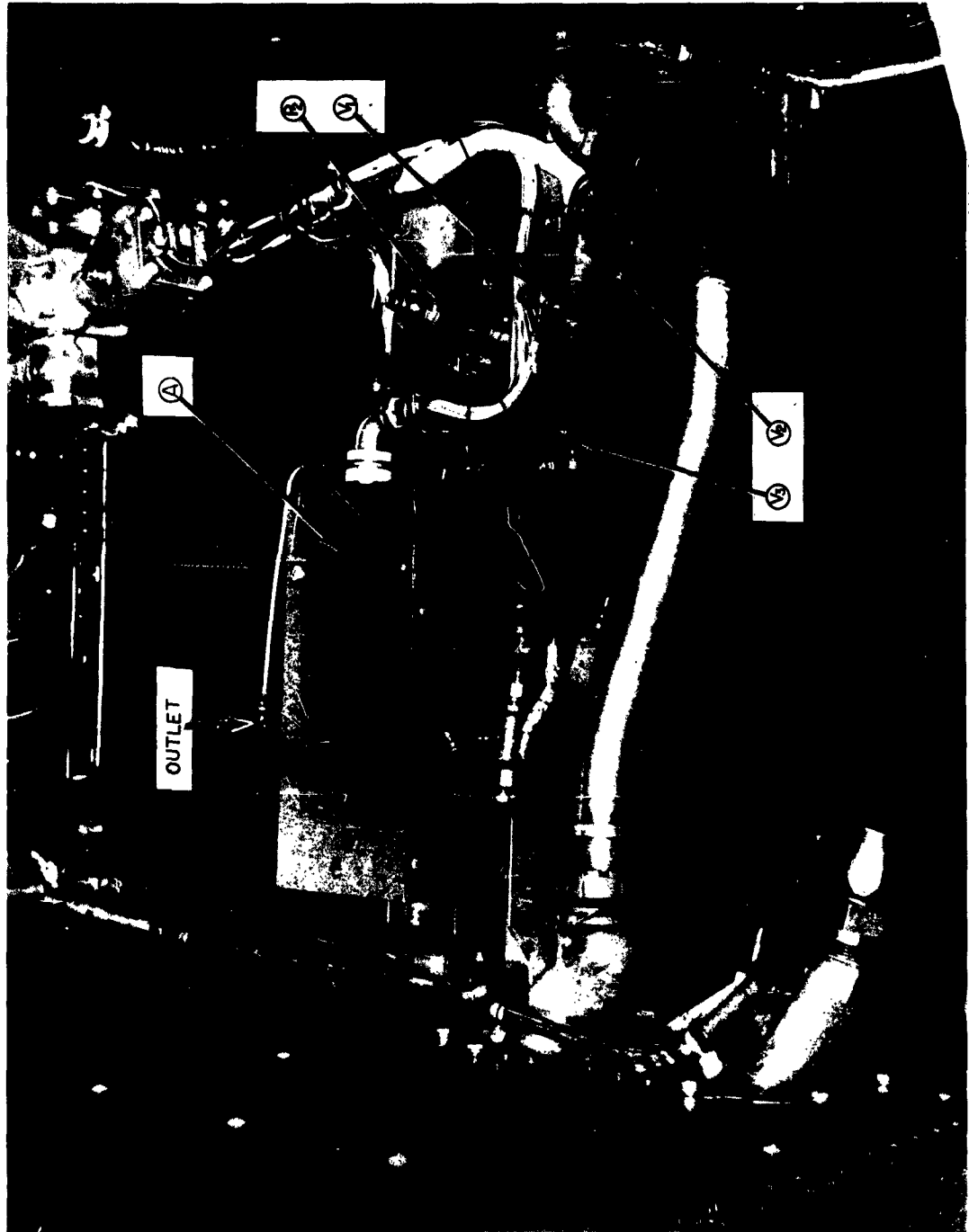


Figure 13. Analyzer for Liquid Water Content Device Mounted in Lower Engine Bay, F-100

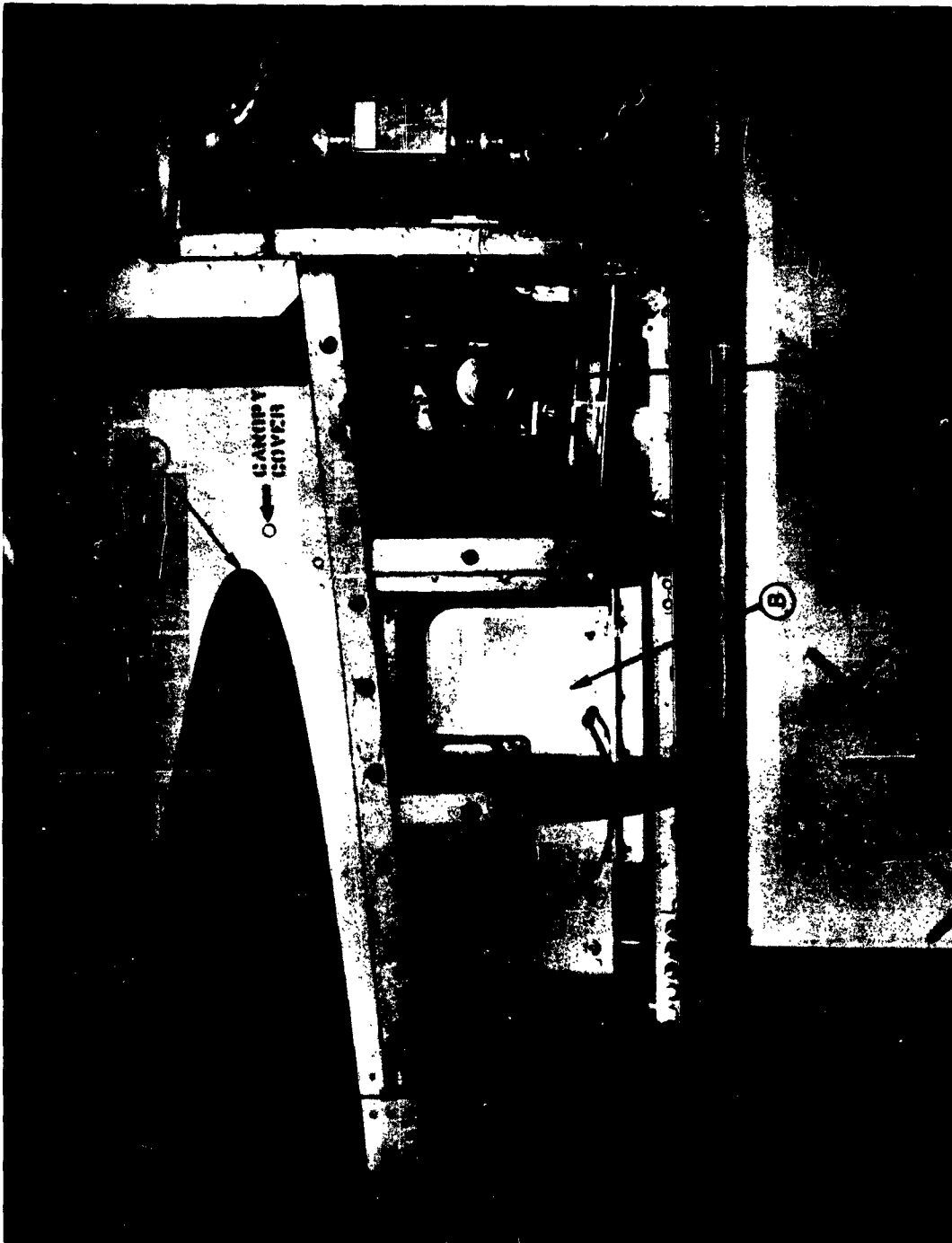


Figure 14. Amplifier for Liquid Water Content Device and Hail Camera Mounted in Fuselage Bay, F-100

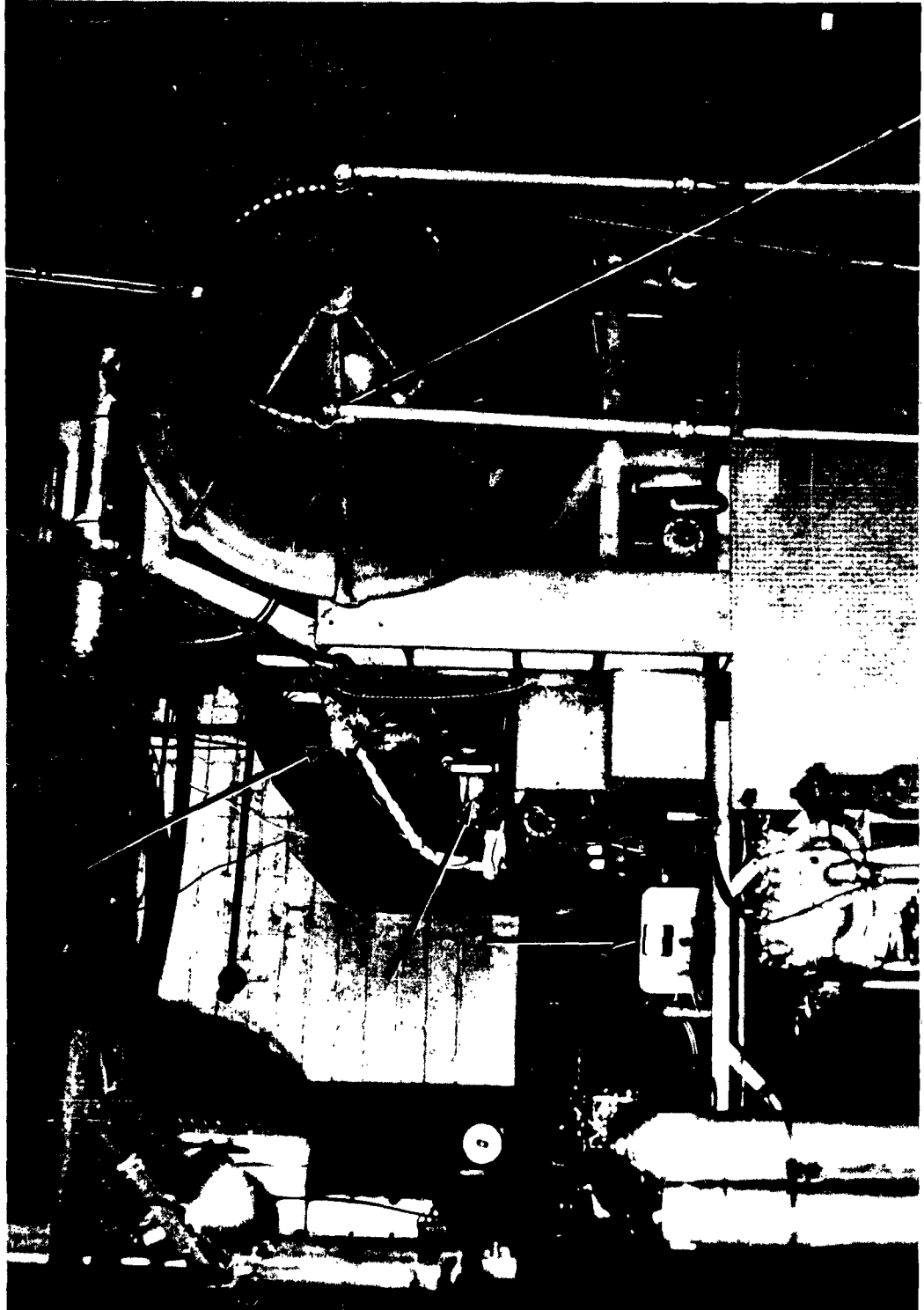


Figure 15. F-100 Engine in Test Cell

Limited data from engine cell tests and other ground and flight runs allow some estimate to be made of accuracy and response. Accuracy, determined by comparing instrument output with measured vapor content on the ground, is estimated at  $\pm 20\%$ . Lag of about 10 seconds occurs when encountering an increasing amount of water; the lag is much greater during decreases in water amounts. The slow response tends to smooth out rapid variations of liquid water encountered during a storm traverse.

#### Cloud Particle Camera

The camera for photographing cloud particles is shown mounted on the F-100 in figure 16 and on the T-33 in figure 1. Figure 17 is a schematic of the system, while figure 18 shows the camera and its components. The camera was carried in a modified external fuel tank on the F-100 and in a modified chaff dispenser tank on the T-33. Both tanks were pressurized to maintain the internal pressure at or below 8000 feet to protect the high voltage components.

A detailed description of the optical and electronic subsystems will be given in a forthcoming ASD Technical Documentary Report. A spark gap mounted at the base of one probe produced a light flash of about one microsecond duration when 22,000 volts were discharged across it. The light was transmitted by suitable optics out the probe, across the gap between the probes, and back through the second probe to the film magazine. If a cloud particle was at the proper location between the probes when the flash went off, a photo of its shadow was recorded on 70mm film.

Magnification of the drops was 16.8 times in the direction of motion and 18.1 times in the direction perpendicular to motion (see figure 19a). This "tearing" effect was caused by a spark gap being of finite length rather than a "point source." The field of view was approximately 0.02 square inch. Depth of field was very small, of the order of one-eighth inch. Particles, though out of focus, were visible all the way across the gap. The test area was located approximately in the center of the space between the probes.

The probes were placed parallel to the airstream to minimize effects of the aircraft on the flow field in the test section. The test section is approximately one pod diameter forward of the tank. The noses of the probes have a fineness ratio of two, also to lessen interference. It is felt that very little concentration or dilution of particle frequency takes place because of interference.

Flash duration was one microsecond at the 50% light intensity magnitude point; however, results indicate the film reacted to only the peak light intensity, reducing the effective flash duration considerably. Note that very little "smearing" of the image is in evidence in figures 19b, c, and d.

The cloud particle photographs shown in figure 19 are representative of all exposures made during the project. Relative motion is shown in figure 19a. The scale for the examples is approximately one inch = 525 microns. There are several interesting things to note in the photographs. First, the particle shown in figure 19a is quite large, almost the largest one found. The altitude at which this photo was made was 35,000 ft but the storm clouds went up to 62,000 ft.



Figure 16. Cloud Particle Camera Mounted on F-100



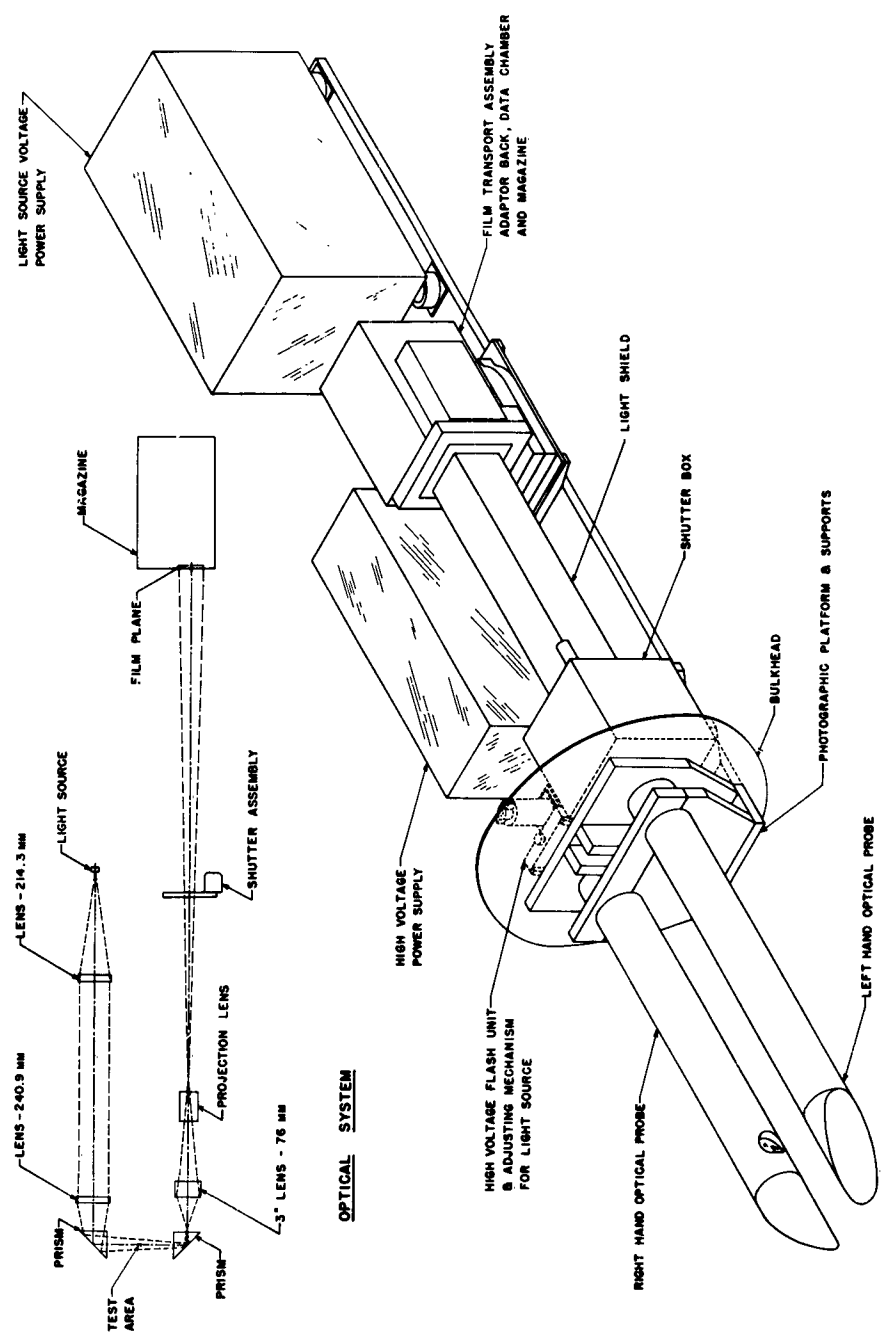


Figure 17. Schematic Drawing of Cloud Particle Camera Components



Figure 18. Cloud Particle Camera Removed From Pod



Figure 19a. Example of Particles Photographed With Cloud Particle Camera

Second, figure 19b shows a particle with "square corners." Other particles in the same picture do not appear to be of the same type as evidenced by the difference in shape. Note the "square" particles at the lower edge of figure 19c, and that the photo was made at a relatively low altitude. Several other particles having this peculiar shape were photographed during the program.

Third, figure 19d was chosen to show a particle shape - irregular - that appeared quite often. It could be, though, that what is seen are two or three individual drops in close proximity. On the other hand, similar shapes were found many other times.

Icing of the external components occurred a number of times during storm penetrations. Ice collected in the aft portion of the prism openings. However, since the light beam "uses" only the center portion of available opening, no difficulty was experienced. Not enough data were collected to evaluate effect of rain in the prism opening. On one flight it appeared that water obscured the field of view, but it could not be verified. Some problems were encountered when two missions were flown in one day and the second closely followed the first. Upon landing after the first flight warm moist air would condense on the camera system. The primary trouble areas were the spark gap, where the moisture would "short out" the discharge; and the optical components, where the moisture would deposit impurities which showed up in a later photographs.

#### Differential Static Pressure

The equipment (figure 20) used to measure differential static pressure was a Rosemount Limited Range Altimeter. This instrument was designed for calibrating static pressure sources of altitude and airspeed systems in USAF aircraft. One mode of its operation was suitable for this program.

Just after turning on the oscillograph recorder, the T-33 pilot closed a remotely-operated valve, trapping a sample of ambient air in a temperature-controlled pressure tank. One side of a sensitive differential pressure transducer was exposed to this sample, the other side to the instantaneous static pressure. Variations of the ambient static pressure from the "trapped" pressure were recorded on the oscillograph.

Accuracy of the differential height (D-value) ranged from  $\pm 80$  ft at sea level to  $\pm 20$  ft at 35,000 ft altitude.

Changes in static pressure sensed by the instrument were caused by actual variation in the pressure and vertical displacement of the aircraft. The effect of the latter was removed by double integrating the normal acceleration and subtracting this figure from the measured pressure variations. The normal acceleration used was uncorrected for either roll or pitch angle.

#### Hail Camera

A 16mm high-speed movie camera, mounted in the right side of the F-100 fuselage (figure 14, Item C, and figure 21), was focused on the black tip of the right external fuel tank. When hail was encountered the instrument operator turned on the camera. It ran at 2000 frames/second, going through 100 ft of film in about two seconds.

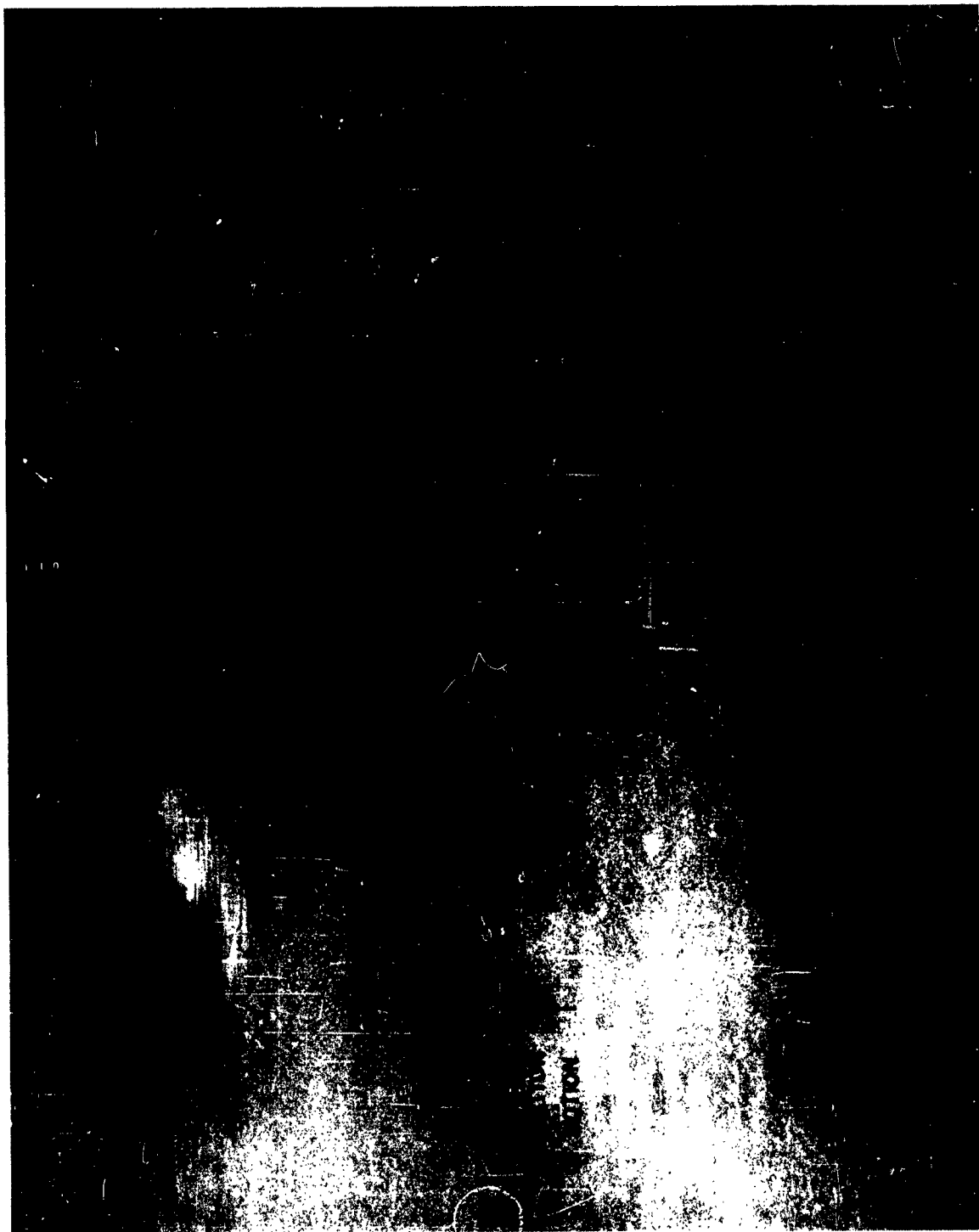


Figure 19b. Example of Particles Photographed With Cloud Particle Camera

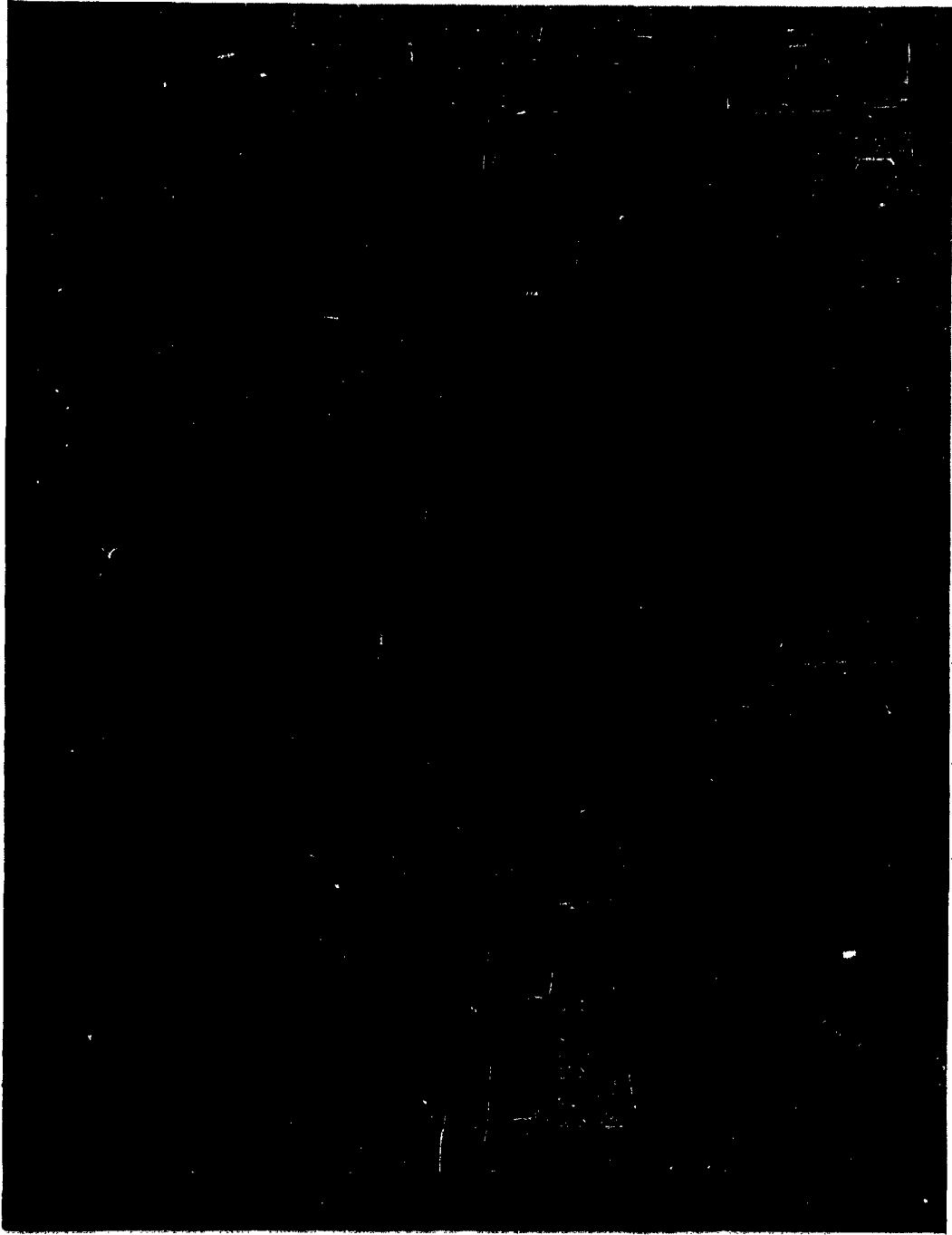


Figure 19c. Example of Particles Photographed With Cloud Particle Camera

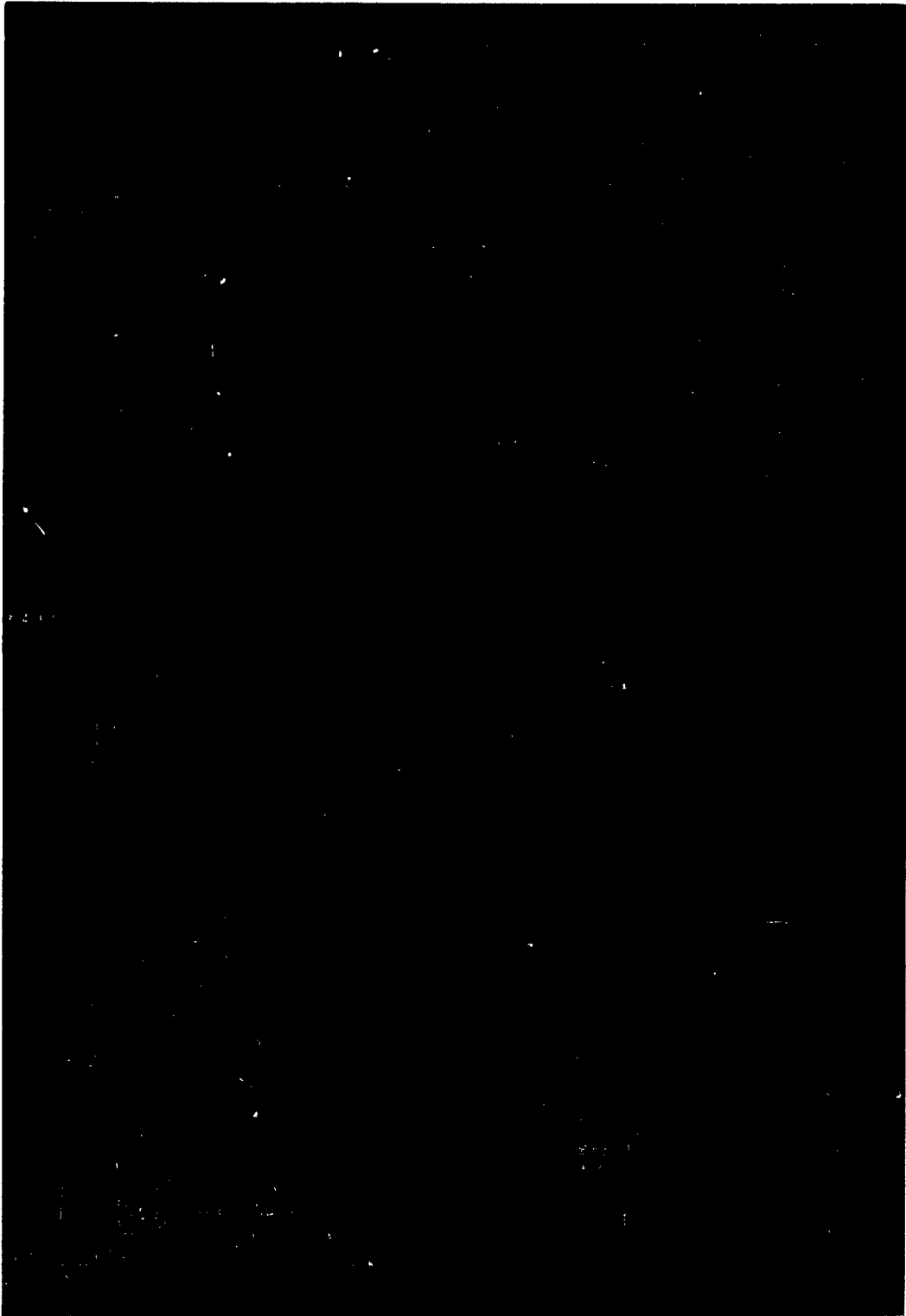


Figure 19d. Example of Particles Photographed With Cloud Particle Camera

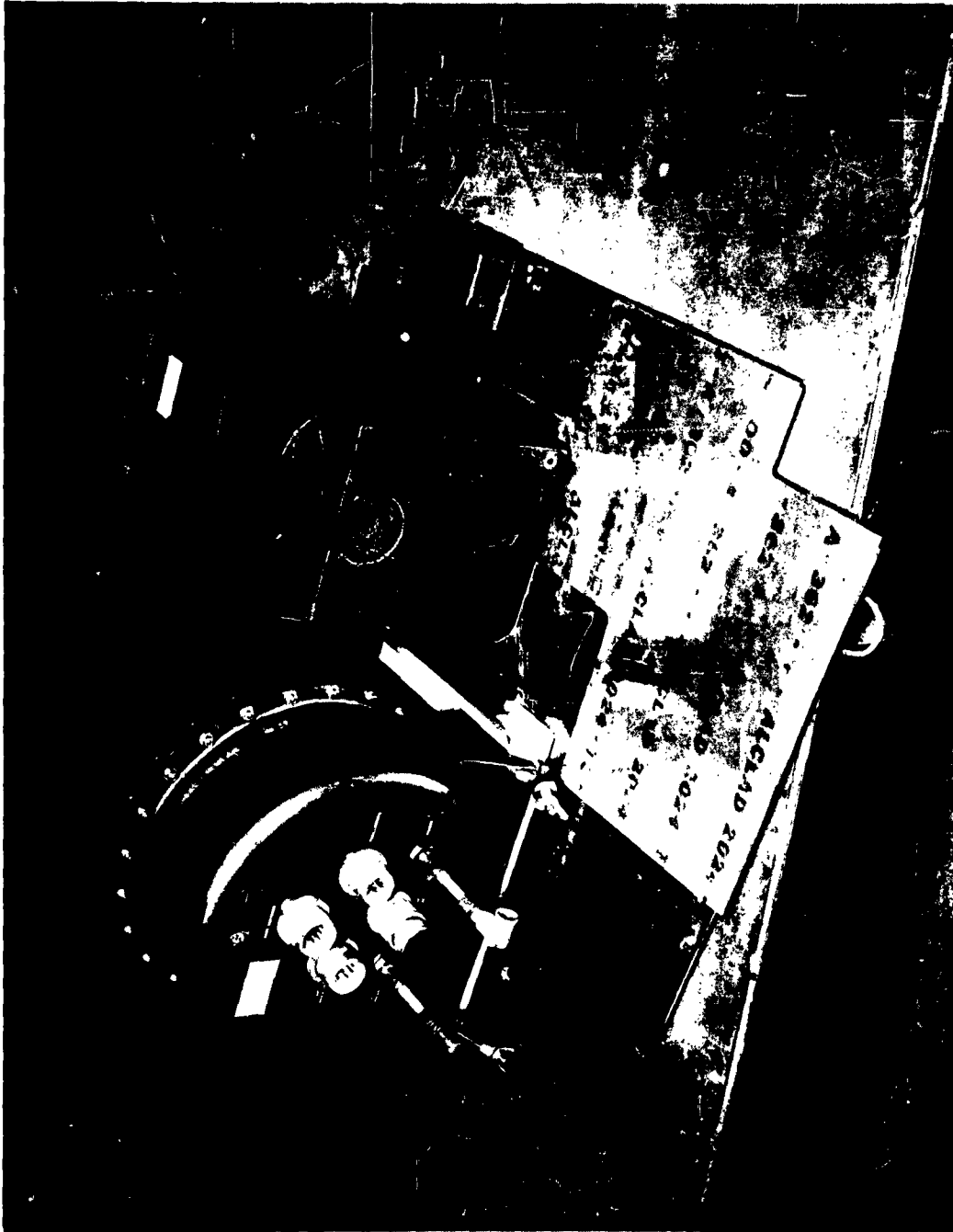


Figure 20. Differential Pressure Equipment Removed From the T-33





Figure 21. Right External Tank and Hail Camera, F-100

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Some hail was photographed. However, even the fast frame speed was not sufficient to stop the motion and all that could be seen was a blur. The hail was observed shattering against the tank, but it could be detected only when it was between the camera and the black surface.

No measurements could be made of size. Shapes could not be distinguished either because of "smear" or because the objects were out of focus. The interesting feature was the seemingly large numbers of particles that appeared during the short exposure time.

### Electric Field Strength

Instruments were carried on the F-100 to measure lateral and vertical components of the external electric field and electric charge on the aircraft. No attempt is made here to describe the equipment, as it was designed, developed, and fabricated by elements of AF Cambridge Research Laboratory.

Figures 22 and 23 show the transistorized components, including a three-channel solid state computer, mounted in the left-hand gun bay. Figure 24 shows one of the field mills mounted on the wing tips (one on each tip). Another mill was on the underside of the fuselage.

### Static Dischargers

Static dischargers of a new design were mounted prolifically over the two aircraft. Three dischargers on each wing and one in the vertical fin of the F-100 were instrumented to record current being discharged (figure 25). The T-33 had instrumented dischargers on the fins of one tip tank.

Primary purpose of the installation was the development of equipment which would allow more favorable communications in high-level static electricity environment. It was also found that the recorded discharge current was a good indicator of cloud entry when the approach was made in clear air. This was particularly true when the cloud was entered from the west or southwest sides. AFCRL personnel also found the recorded current to be an aid in interpreting data from the electric field strength instrumentation.

### Cockpit Controls and Other Items

Figure 26 shows the instrument operator's control panel in the rear seat of the F-100. Figure 27 shows the indicator and selector switch for monitoring temperatures in the water vapor analyzer sample handling system (Item A) and the balance potentiometer and indicators for the electric field gear (Item B). The control panel for the T-33 pilot is shown in figure 28. Controls for the on-board tape recorder were on the opposite side of the cockpit. The control box for the differential pressure device is shown in figure 29. The needle in the box was not used in the test operating mode.

What could be seen of the instrumentation in the back seat of the T-33 is illustrated by the oscillograph shown in figure 30. The oscillograph on the F-100 aircraft was in the nose compartment (figure 31).

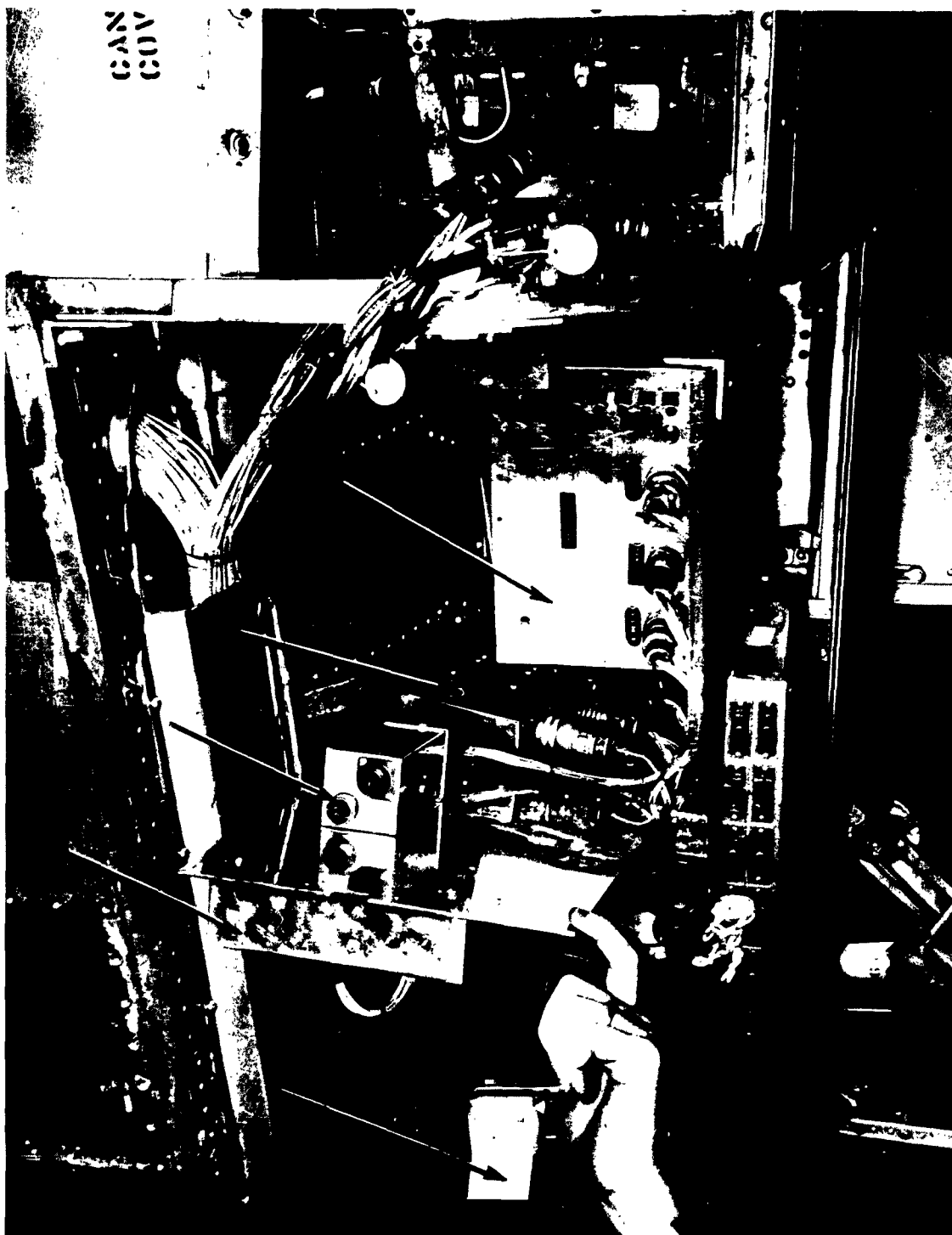


Figure 22. Electric Field Strength Equipment, F-100

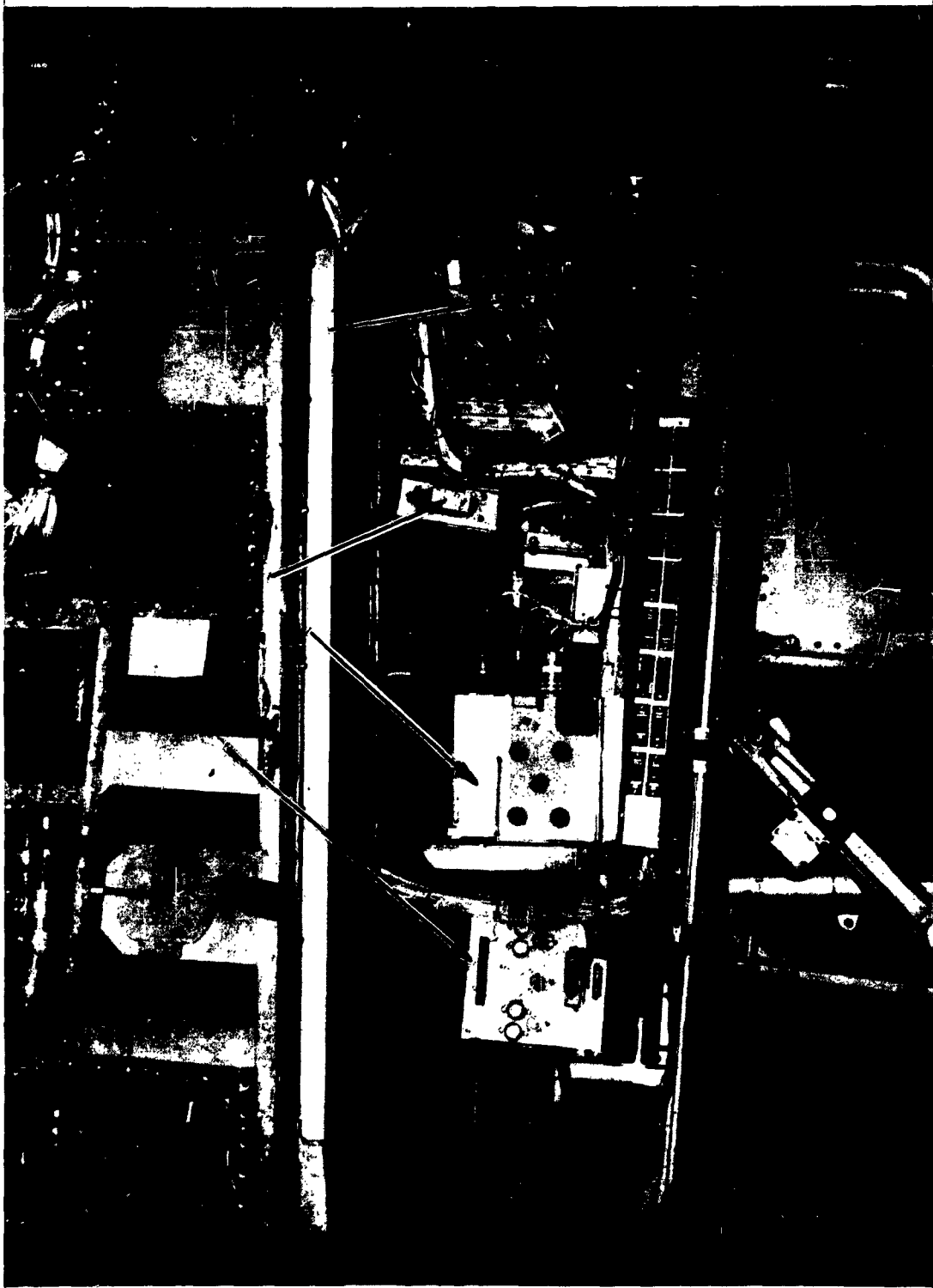


Figure 23. Electric Field Strength Equipment, F-100



Figure 24. Field Mill Mounted in Left Wing-Tip of F-100

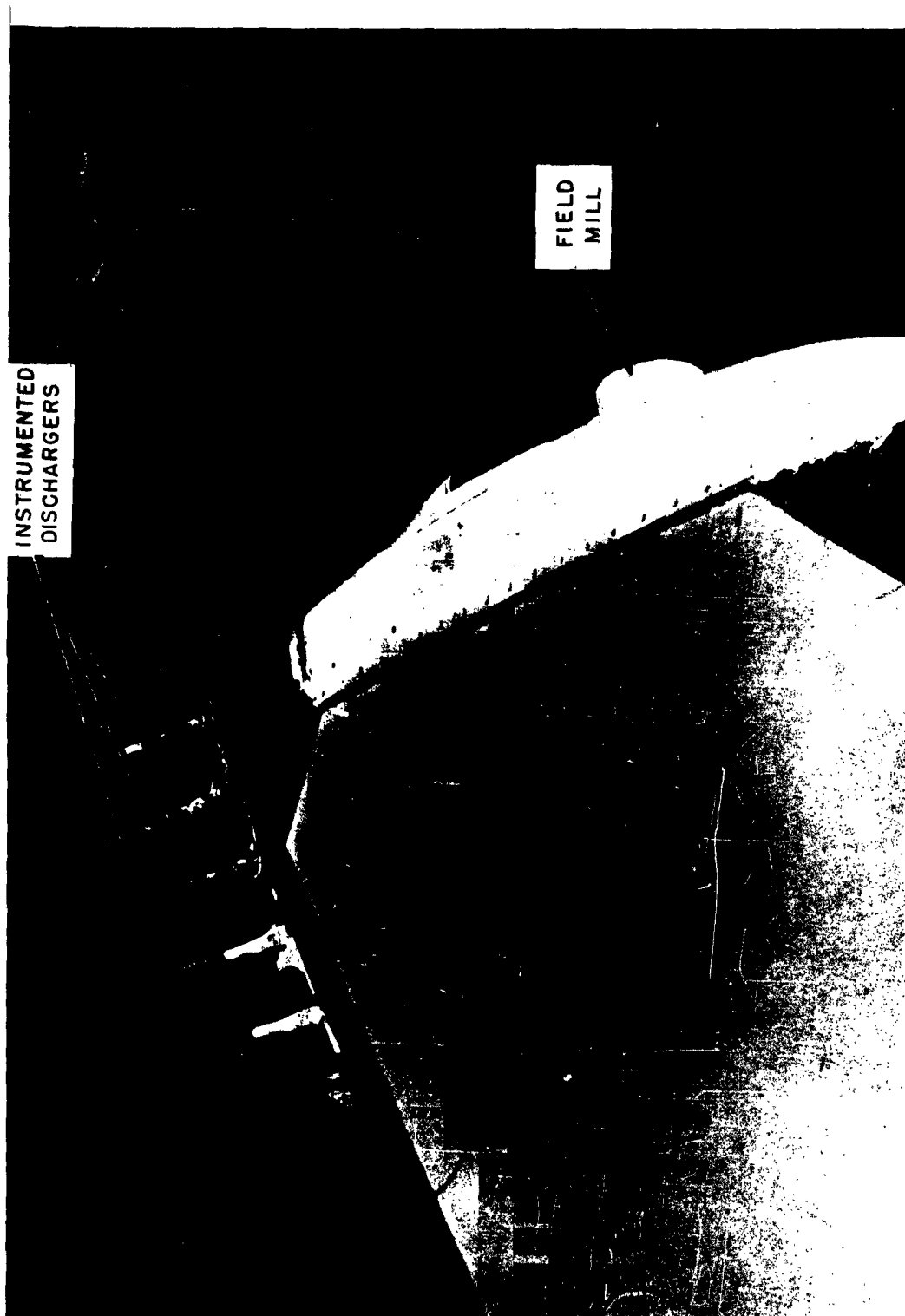


Figure 25. Static Discharger on Left Wing-Tip of F-100

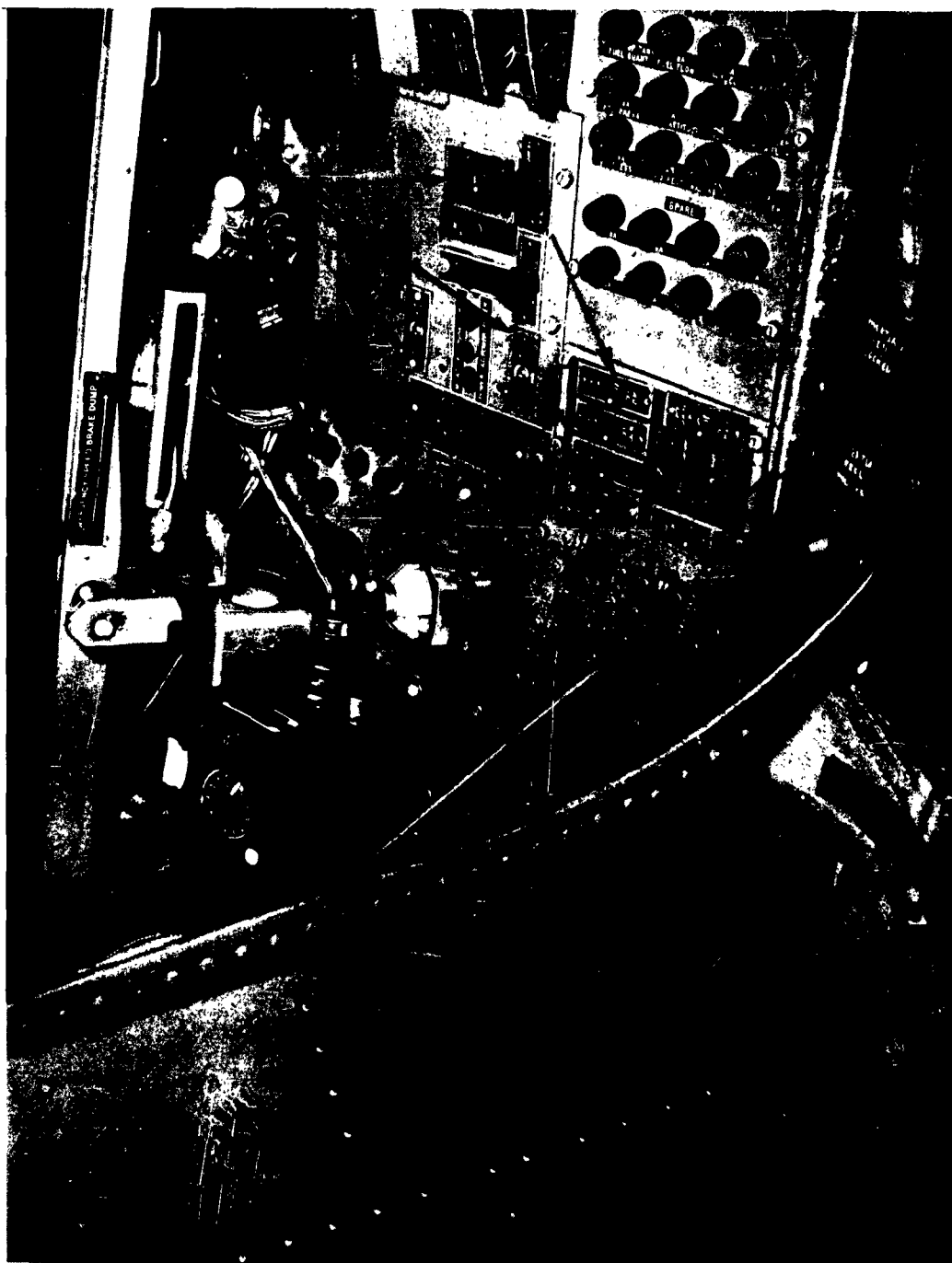


Figure 26. Test Instrumentation Controls on Left-Hand Console in Rear Seat of F-100



Figure 27. Test Instrumentation Control on Flight Instrument Panel, F-100



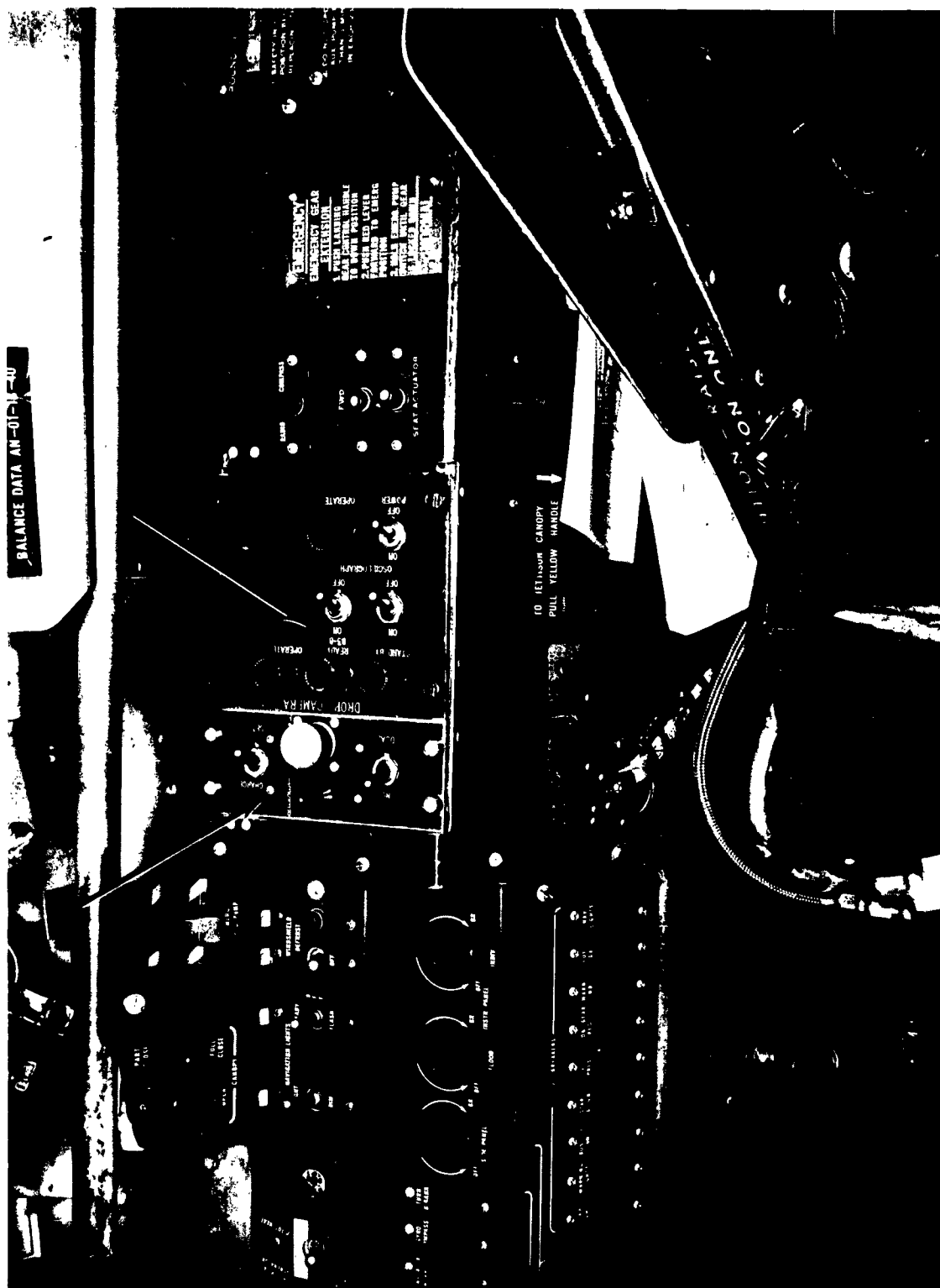


Figure 28. Test Instrumentation Controls on Right-Hand Console of T-33

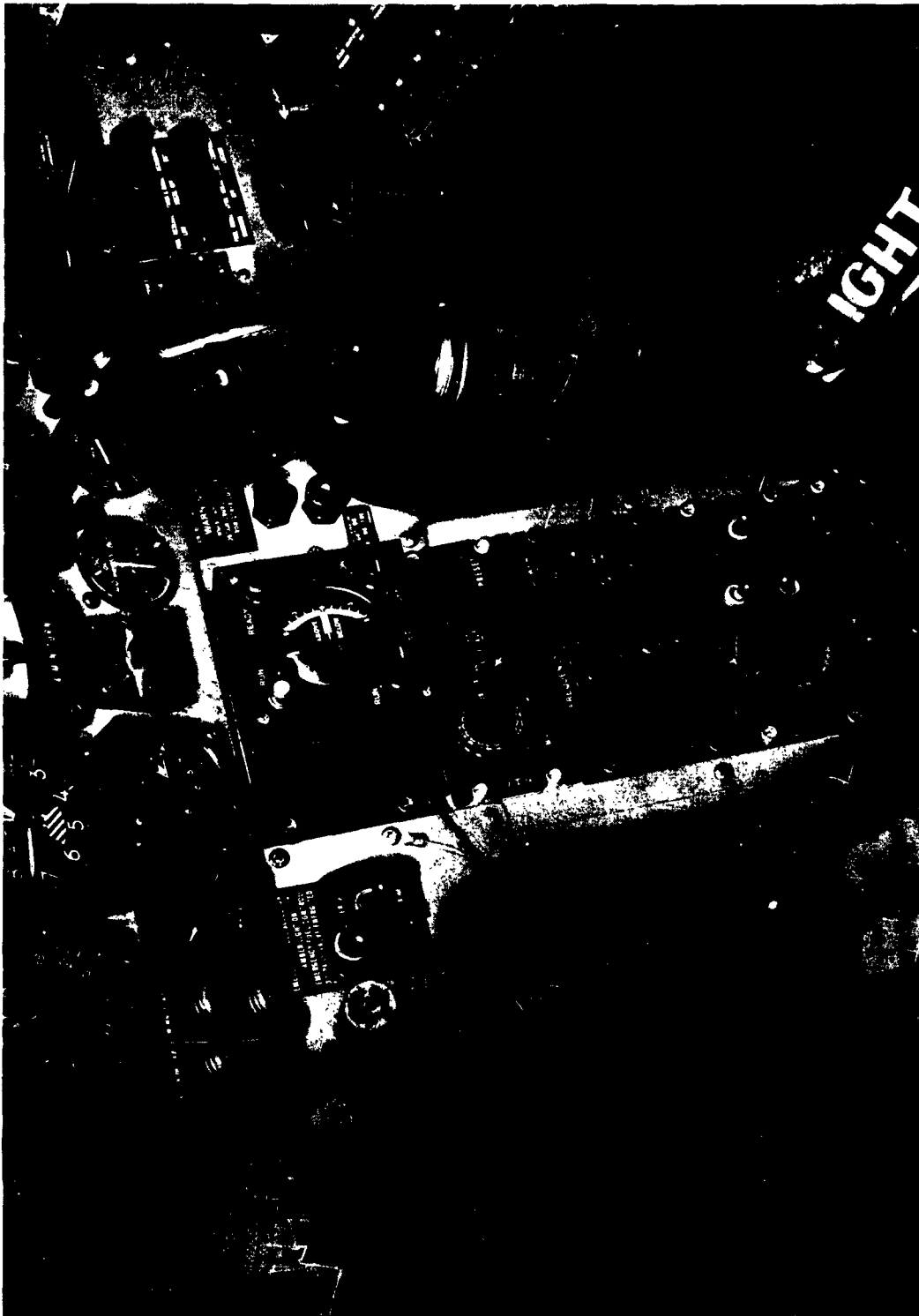


Figure 29. Test Instrumentation Control on Flight Instrument Panel, T-33

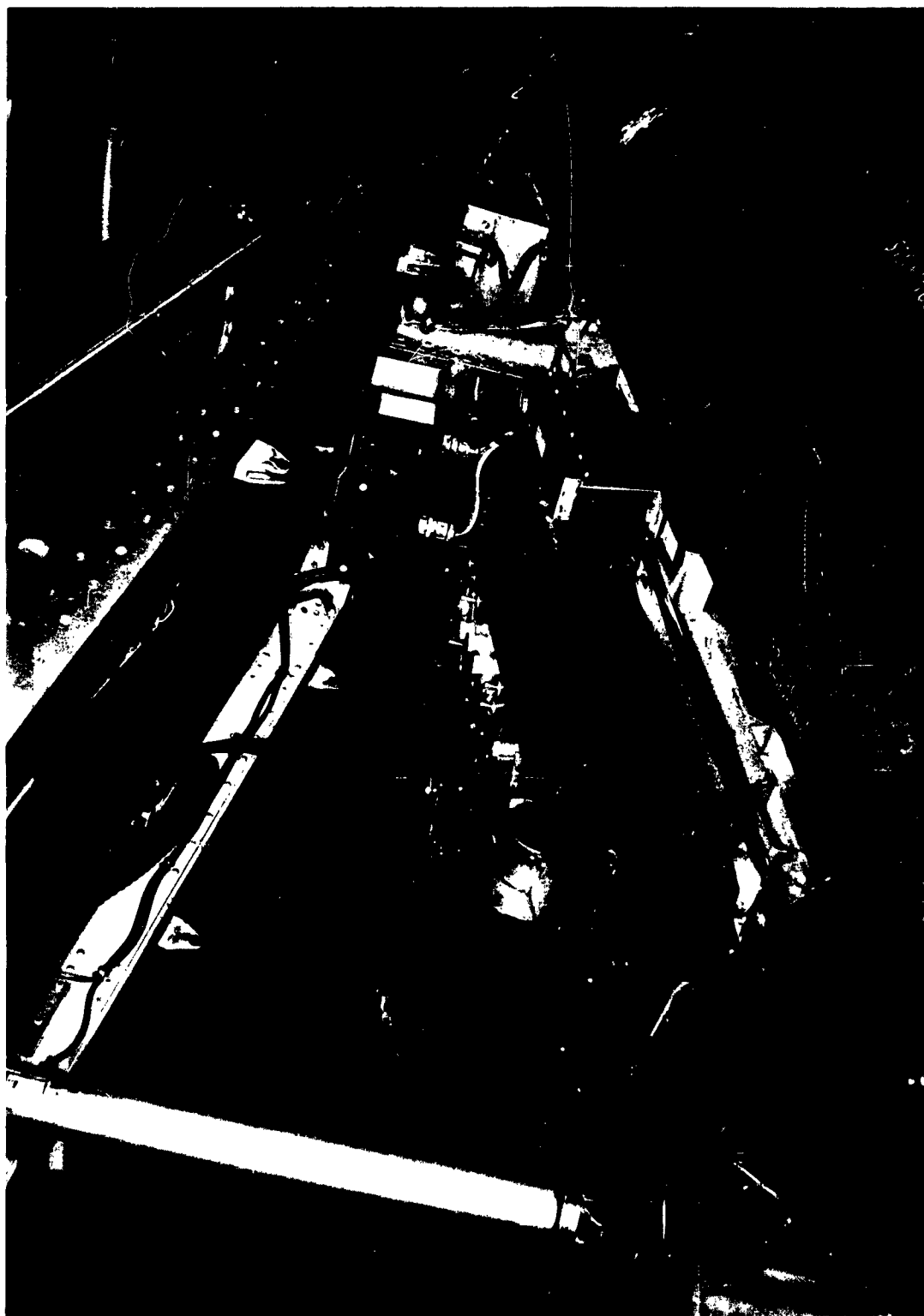


Figure 30. Oscillograph in T-33

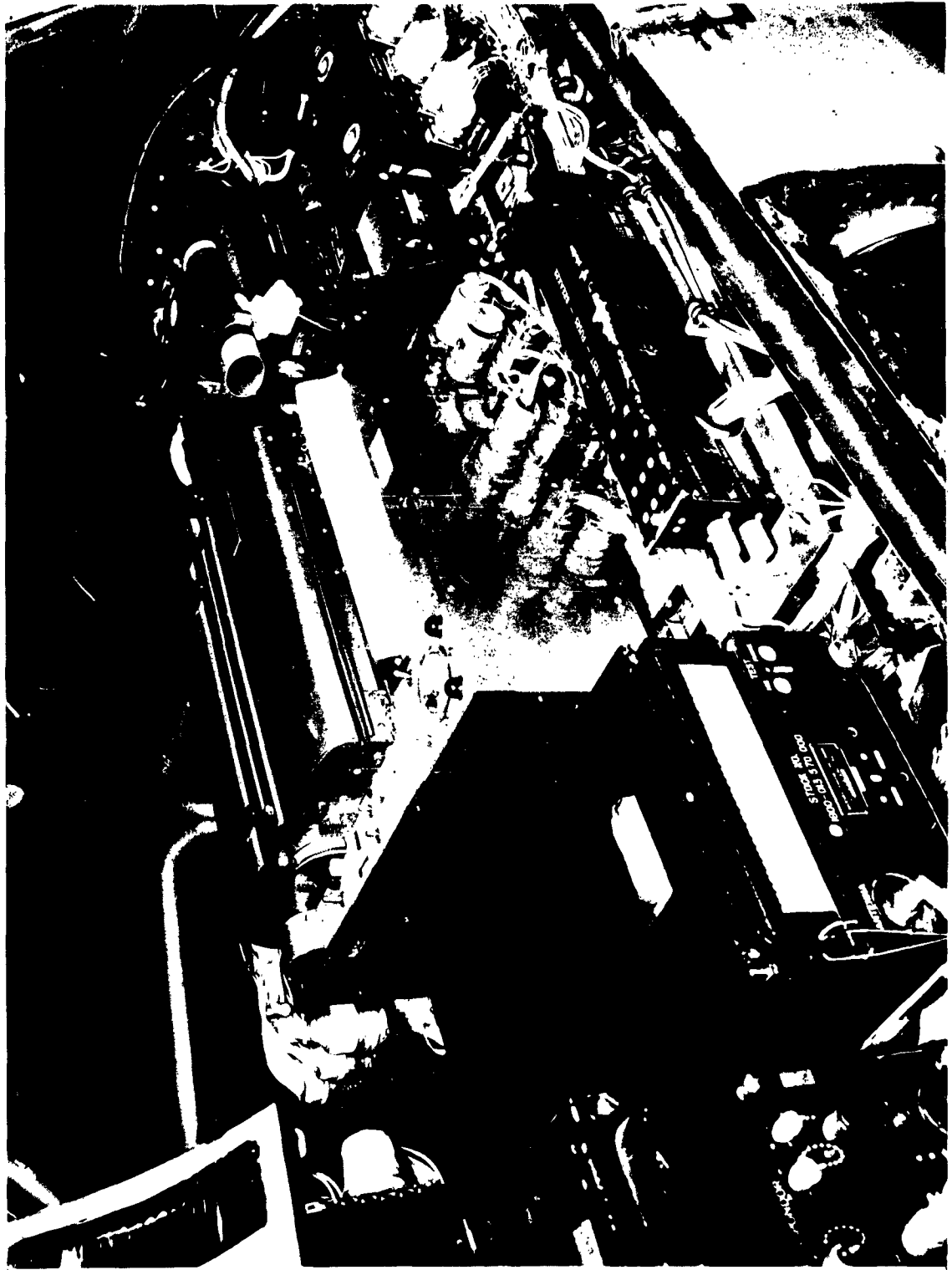


Figure 31. Oscillograph in F-100

## FLIGHT OPERATIONS AND AIRCRAFT DAMAGE

The F-100 made 41 storm penetrations on 9 flights, accumulating approximately 168 minutes of recorded data. The T-33 had 63 traverses on 11 flights, gathering about 290 minutes of data.

Handling characteristics of both aircraft were satisfactory. Primary disturbances were in roll and inertial coupling induced yaw. Standard thunderstorm penetration procedures (airspeed established prior to storm entry, then constant power, constant attitude, and constant heading) were used for most of the storm traverses. At times headings were changed to direct the aircraft into different areas of the storm or to correct for wind. The altitude was also closely monitored because at times the two aircraft penetrated the same storm at the same time with 5000 ft vertical separation.

Heavy precipitation induced compressor stalls in the F-100. Continuous ignition was energized whenever stalls started. There was never any degradation of engine performance.

A hot-air heated pitot head, installed on the F-100 after the original one was broken off, proved to be unsatisfactory. Enough heat was not available to keep the pitot tube free of ice in the heavy precipitation areas. Electrically heated pitot tubes were required.

Figure 32 shows typical damage to dischargers caused by lightning and/or heavy current discharge. All of the dischargers shown were damaged during one flight through storms.

The T-33 was particularly susceptible to hail damage because of the soft metal used on much of the aircraft, straight wings, and blunt-nosed tip tanks. Figures 33, 34, 35, 36, and 37 show typical hail damage to the T-33. The vertical fin and antenna covering damage occurred during one flight (figures 33 and 35). Note the holes torn in the intake duct leading edge in figure 34. It was interesting to observe that the cooling louver on the left side of the T-33 (figure 37) was repaired/replaced three times, while the one on the right side did not sustain any damage at all.

Very little damage occurred to the F-100 because of hail. Figure 38 shows an antenna covering on the leading edge of the inlet duct. This piece was replaced by heat-treated aluminum. A new type of rain erosion shoe was installed on the TACAN antenna on the vertical fin. The only damage occurring to it resulted from a hail ball striking its lower edge (figure 39) and allowing the airstream to peel back the covering.

The nose fairings on the cloud particle camera tanks were constructed of wood. Ice crystal, rain, and hail erosion eventually called for a protective covering. The sheet metal first used was unsatisfactory, figure 40, and stainless steel replaced it, figure 41.

Instrumentation wiring from the fuselage to the left wing was abraded (figure 42) when a gasket at the leading edge of the wing root was worn away (Item A, figure 14). Precipitation particles sweeping along the fuselage entered the opening and caused the damage.



Figure 32. Damaged Static Dischargers

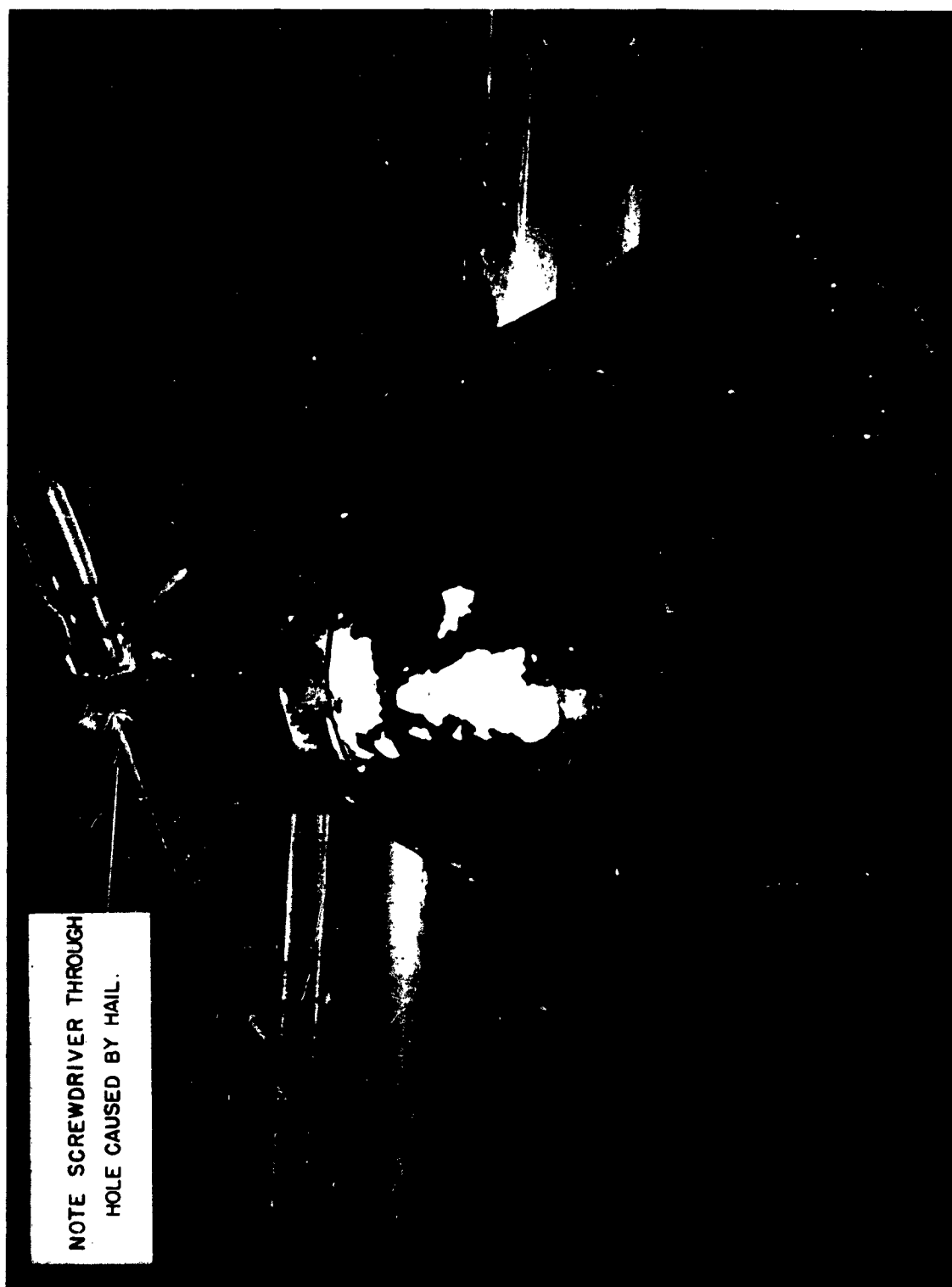


Figure 33. Damaged Antenna Covering on Nose of T-33



Figure 34. Damaged Left Intake Duct of T-33





Figure 35. Damaged Vertical Fin of T-33



Figure 36. Damaged Tip Tank of T-33



Figure 37. Damaged Louver on Left Fuselage of T-33



Figure 38. Damaged Antenna on Intake Duct of F-100

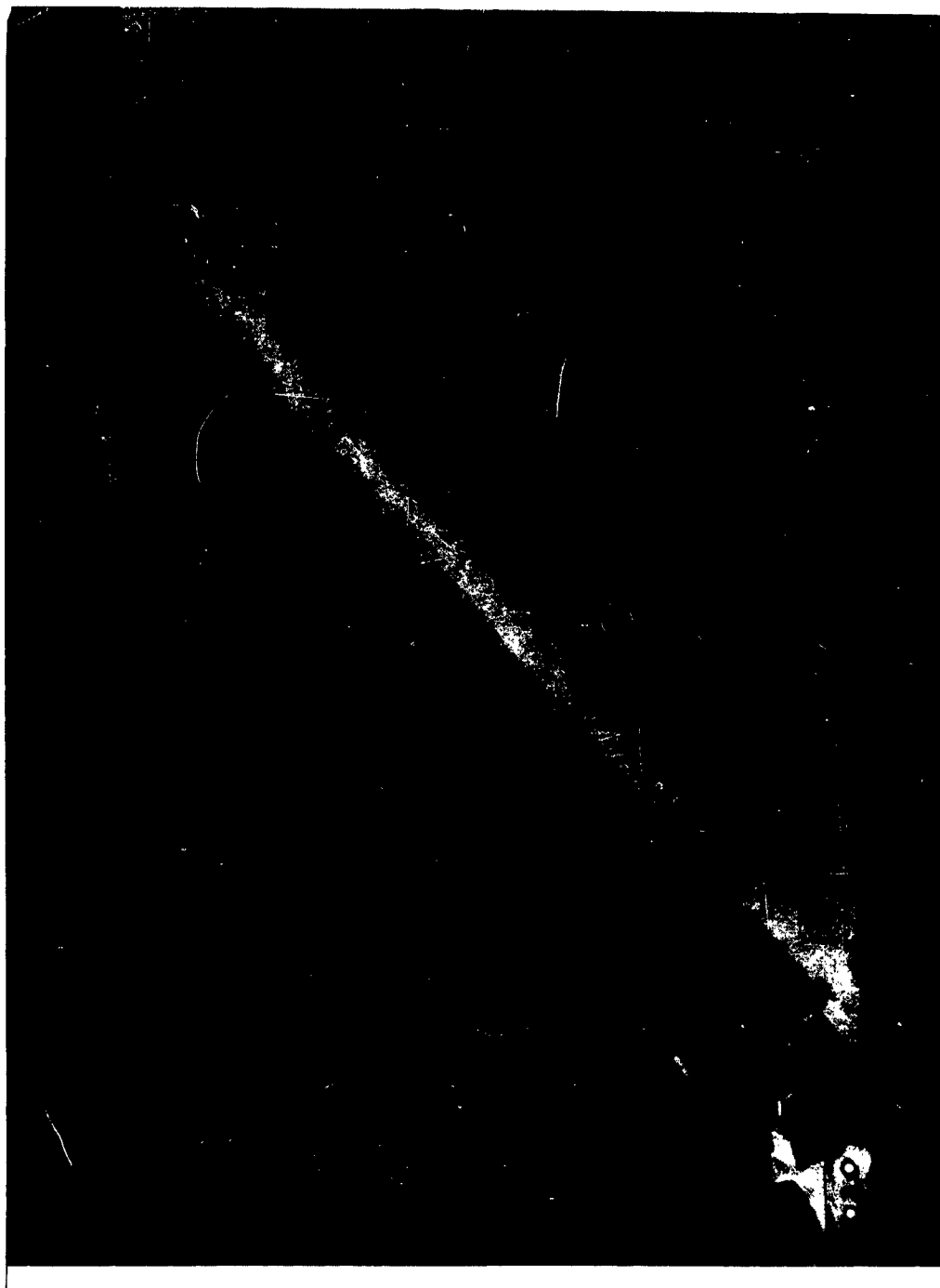


Figure 39. Damaged Vertical Fin Antenna Covering on F-100



Figure 40. Damaged Sheet Metal Covering on Nose Fairing of Cloud Particle Camera



Figure 41. Stainless Steel Covering on Nose Fairing of Cloud Particle Camera

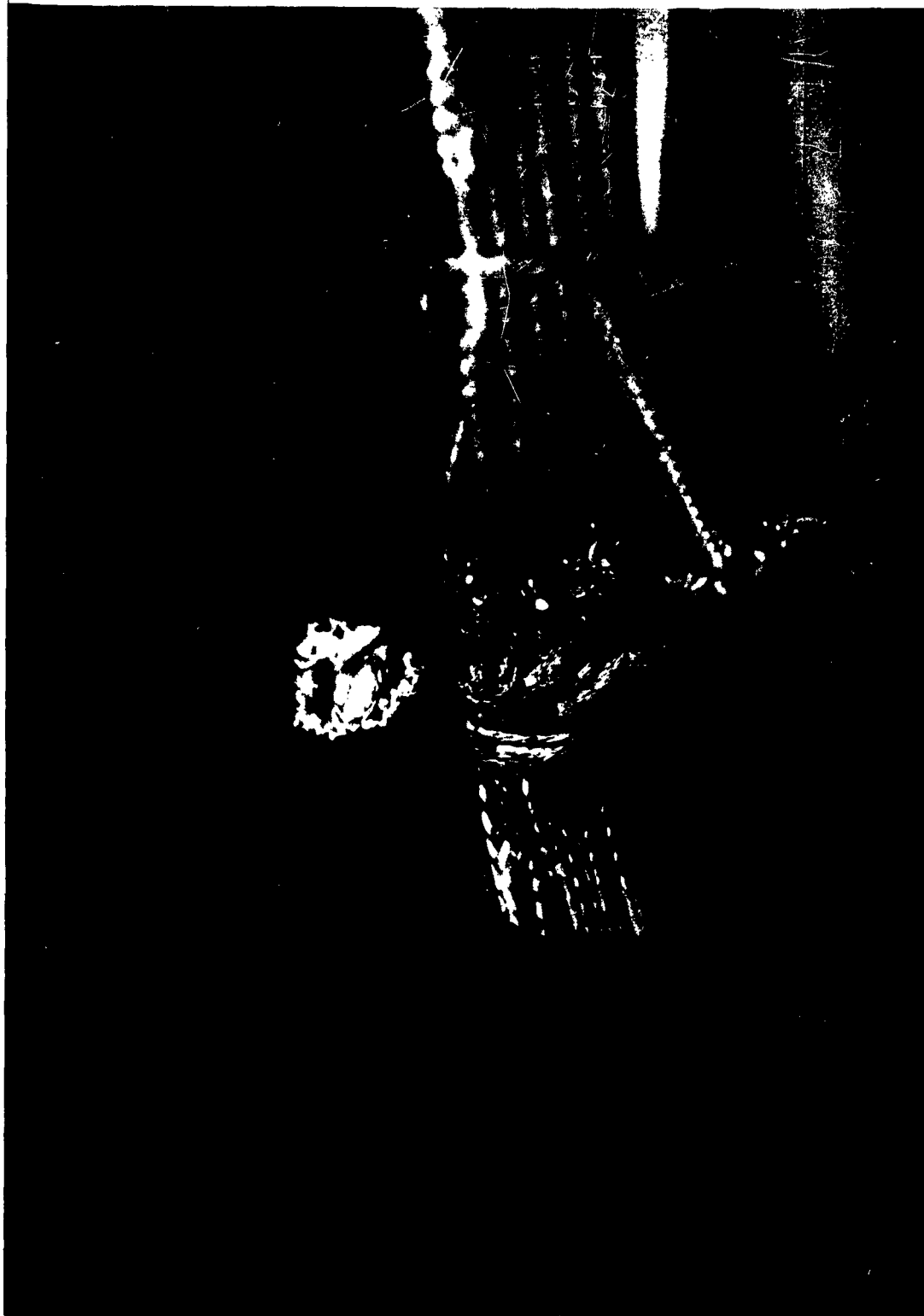


Figure 42. Instrumentation Wiring Damaged by Water and Vibration When a Wing Root Fairing Failed



## INSTRUMENTATION SYSTEM IMPROVEMENT PROGRAM

The following programs are underway, or are planned, to increase the reliability, accuracy, response rate, and overall data quality of the instrumentation system.

**Cloud Particle Camera**

Heaters have been installed to help eliminate the condensation. The spark gap housing has been sealed to prevent moisture from shorting the gap. The rate at which exposures can be made has been increased to one per second.

**Gust Velocity:**

The vane support system is being redesigned to reduce frictional damping. A new method of sensing vane rotation will be utilized to provide better accuracy. New gyros are being obtained to reduce errors due to drift and to allow data reduction to account for long wave length drafts. The boom for the vanes will be made longer, stronger, and stiffer.

**Airspeed and Altitude:**

More accurate and complete calibrations will be conducted.

**Differential Pressure:**

A new device is being obtained which does away with the necessity for physically trapping a sample of air. The new system will be more accurate.

**Temperatures:**

Both heated and unheated sealed element probes will be used, along with two different probe designs. A more accurate and complete determination of recovery factor will be accomplished.

**Hail Mass:**

A more accurate calibration will be conducted. The web thickness will be increased to reduce the noise level in the recording trace. The protective shield has been strengthened.

**Liquid Water Content:**

An attempt will be made to have the device installed on an engine in a test cell to determine its accuracy and responsiveness. The time required to take the sample from the engine to the analyzer will be decreased by utilizing a faster flow rate. Means of more closely maintaining pressure in the analyzer will be devised.

**Miscellaneous:**

A tape recorder will be installed in each aircraft to record pilot's and observer's comments. This method produces more complete descriptions than does having the comments broadcast over the radio to be recorded on the ground. For use in conjunction with the recorders, an elapsed time counter will be installed so that comments can be correlated with elapsed and clock time.

## OBSERVATIONS

The following observations result from the 1962 flight test program:

- (1) It is possible, though difficult, to measure a number of meteorological variables simultaneously from a jet aircraft flying in thunderstorms.
- (2) A primary consideration, which resulted in certain compromises, was that to make a device capable of sensing large magnitudes, e.g., liquid water content, the measuring system produced inaccurate, slow response data.
- (3) Calibration of instruments, and design of the instruments themselves, produced the most difficulty in making a successful program.
- (4) As a result of item (3), one aircraft should remain in a test configuration for an extended period of time and personnel should be assigned to a complete calibration program.
- (5) The three new measuring techniques (liquid water content, cloud particle size, hail mass) designed by ASD provided useful information.

## REFERENCES

1. Roy Steiner and Richard Rhyne, Some Measured Characteristics of Severe Storm Turbulence, NASA Langley Research Center, Presented to American Meteorological Society Conference on Severe Storms, February 1962.
2. Capt Russell Hodges, Replacement Gust Vane, Unpublished study, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, January 1962.
3. Kermit G. Pratt, A Revised Formula for the Calculation of Gust Loads, NACA TN 2964, June 1953.
4. Lt Barton Underwood, Coefficient of Restitution Experiment, Unpublished report, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, April 1962.
5. John Lee and Francis Sears, Thermodynamics, Reading, Massachusetts, Addison-Wesley Publishing Company, 1955.

Aeronautical Systems Division, Dir/Flight Test, Wright-Patterson AFB, Ohio.  
Rpt No. ASD-TDR-63-231. AIRBORNE INSTRUMENTATION SYSTEM FOR MEASURING METEOROLOGICAL PHENOMENA INSIDE THUNDERSTORMS. Final report, May 63, 59p. incl illus. and refs.

Unclassified Report

Equipment to measure meteorological phenomena inside thunderstorms was designed, fabricated, installed, and operated in two jet aircraft in conjunction with the National Severe Storm Project in Oklahoma City, the Oklahoma. Devices which were used for the first time in this environment were those

( over )

to continuously measure liquid water content, electric field strength, and hail mass, and to photograph cloud particles. Other parameters recorded were normal acceleration, vertical gust velocity, temperature, and differential static pressure. The data collected during the ASD flight test program are archived with the U. S. Weather Bureau and can be obtained through the National Severe Storm Project.

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2. Meteorological phenomena, measuring
3. Thunderstorms
4. F-100F Aircraft-Measuring Meteorological Phenomena
5. T-33 Aircraft-Measuring Meteorological Phenomena

I. AFSC Project 8620,  
Tasks 862001.  
862005

- II. G. P. Roys, 1st Lt, USAF
- III. Aval fr OTS
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